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THERMOELECTRIC MATERIALS

Final Report

Contract No. NObs 78326

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THERMOELECTRIC MATERIALS

FINAL REPORT

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ABSTRACT

Three hundred twenty-three oxide, silicate, and metal hydride combinations were prepared and fabricated into test specimens by a variety of forming and firing techniques. Of these combinations, 309 were examined electrically for Seebeck effect and resistivity from 600 to 1200°C; the remaining few failed in test.

Amongst electronic semiconductors were the following n-type examples. Titanium dioxide plus $2.0^m/o$ Nb_2O_5 exhibited a Seebeck coefficient of -400uv/°C and resistivity of 0.1 ohm-cm over the entire temperature range of test. Barium titanate plus $0.5^m/o$ Nb_2O_5 had a Seebeck coefficient of -1700μv/°C at 750°C increasing in magnitude to -3000μv/°C at 1225°C; the resistivity of this composition is unknown but is certainly greater than 5 ohm-cm. No p-type electronic semiconductor with consistent carrier type over the entire temperature range of test was developed.

Positive Seebeck coefficients of considerable magnitude were developed in ionic conductors; ZrO_2-7^m/o Y_2O_3 solid solution plus $10^m/o$ Nb_2O_5 exhibited a Seebeck coefficient of +1000μv/°C at 800°C rising to +1600μv/°C at 1100°C. The electrical resistivity of this composition was also greater than 5 ohm-cm. In general, most oxide semiconductors examined were found to be ionic conductors; Li_2TiO_3 was the singular example of such a material.

None of the compositions tested gave indication of truly efficient conversion of heat to electricity; the above TiO_2 plus $2.0^m/o$ Nb_2O_5 had an approximate figure of merit of $7.0 \times 10^{-5}/°C$.

INTRODUCTION

This final report describes work performed during the period Jan. 1960 to Aug. 1963 under Contract No. NObs 78326 (Index Nos. SR-010024-1BR and SR-007-12-01). The Contract Administrator was Mr. B. B. Rosenbaum, Code 342B, Bureau of Ships, Department of The Navy.

The ultimate objective of this work was the direct conversion of thermal to electrical energy using the Seebeck effect. This method of energy conversion is of interest to the Bureau of Ships for silent, maintenance-free ship-board and remote surface installations. Materials for this thermoelectric conversion were desired for operation in the temperature range from atmospheric ambient to approximately 1700°C. The work reported herein, however, was limited to certain more immediate goals. Only polycrystalline ceramic materials were investigated and the investigation itself was of a preliminary nature. Further development work was to be undertaken only if warranted.

The specific material nature of this work had its origin in a Research Proposal submitted by this laboratory to the Bureau of Ships on 1 May 1959. The examination of materials was limited to a broad, screening type evaluation, which was more extensive than intensive. The approach to the problem was as follows. For the temperature range of interest, 700°C to 1300°C, the most favorable materials were considered to be those refractory oxides and silicates which exhibit the property of, or potentiality for, semi conduction. For simplicity, foreign atom metal oxide "doping" was employed to effect semi-conduction by the "controlled valency effect". Fabricated materials were then screened by electrical measurements; resistivity and Seebeck Coefficient were measured as a continuous function of temperature from 600°C to 1250°C. As a preliminary criterion of usefulness, the square of the Seebeck coefficient divided by the electrical resistivity was used to decide if the thermal conductivity should be determined. If the latter was warranted, the thermoelectric efficiency was calculated; this needed doing for only one material.

The work covered by this report was under the general supervision of Dr. Stephen F. Urban, Director of Research. Material preparation, under the guidance of William J. Baldwin, Chief Ceramist, was done by Robert Peters, Jerrald L. Bliton, Harold Olander, Eugene J. Derefinko, Mrs. J. Cologgi, Chester Winiarski, and Joseph A. Vilardo. The design and construction of electrical measuring equipment and the actual measurements and calculations, under the guidance of Ernest G. Graf, Chief Physicist, were carried out by Truman C. Rutt, Anthony D. Janulionis, Eugene J. Derefinko, Joseph J. Goslin, and Joseph A. Vilardo.

Robert Peters wrote the portion of this report that covers material preparation and fabrication, Eugene J. Derefinko wrote the portion that deals with electrical instrumentation and measurement; they also prepared the tabulations and illustrations.

SUMMARY

Certain specific results of this work are collected below under "Conclusions"; the most notewhorthy of these are presented in accompanying illustrations. The total remaining results are given in an Appendix of three tables. The "Conclusions" are drawn from observations on approximately 20 compositions; interpretation is confined to the few principles known to apply to the type of materials under investigation. The "Recommendations" following, are prognosticative in nature but very practical in origin.

A satisfactory oxide ceramic composition for efficient conversion of heat to electricity did not evolve from the present work.

Conclusions

Titanium dioxide, when modified by addition of from 1.0 to 5.0^m/o Nb_2O_5 and Ta_2O_5, is a moderate n-type thermoelectric having a Seebeck coefficient of $-400\mu v/°C$ from 600 to $1200°C$. The Nb_2O_5 additions have an electrical resistivity of approximately 0.1 ohm-cm while that of the Ta_2O_5 additions is about 0.5 ohm-cm. $TiO_2 + 2.0^m$/o Nb_2O_5 has an approximate figure of merit of $7.0 \times 10^{-5}/°C$.

Niobium pentoxide appears to be a universal dope for conversion of oxide ceramics to thermoelectric semiconductors. In addition to TiO_2, there are $CeO_2 + 4.0^m$/o Nb_2O_5 exhibiting $-500\mu v/°C$ and 1.5 ohm-cm, and $BaTiO_3 + 0.5^m$/o Nb_2O_5 exhibiting -1700 to $-3000\mu v/°C$ and resistivity greater than 5 ohm-cm. Amongst materials having a positive Seebeck coefficient, 10.0^m/o Nb_2O_5 added to $ZrO_2 - 7^m$/o Y_2O_3 solid solution effects an ionic p-type thermoelectric exhibiting +1000 to $+1600\mu v/°C$ and resistivity greater than 5 ohm-cm.

Oxide ceramic thermoelectrics tend to be ionic conductors, particularly those with positive Seebeck coefficients. In addition to the ZrO_2-based compositions as mentioned above, Li_2TiO_3 with additions of oxides of a wide range of oxidation states appear, with one exception, to be ionic conductors. From 900 to $1200°C$ $Li_2TiO_3 + 5.0^m$/o CeO_2 has an average Seebeck coefficient of $+1400\mu v/°C$ and an average resistivity of 25 ohm-cm. The orthochromites of lanthanium and yttrium are also ionic with +500 to $+1100\mu v/°C$ Seebeck coefficient and resistivities down to 1 to 2 ohm-cm.

High temperature p-type electronic semiconductors are extremely difficult to achieve using oxide ceramic materials. All such compositions prepared by controlled-valency doping become intrinsic at high temperature. On the other hand, titanium-containing high dielectric constant insulators are readily converted to n-type electronic semiconductors with appreciable negative Seebeck coefficients; the Nb_2O_5-doped $BaTiO_3$ above is the prime example.

Structurally, the most favorable materials investigated were based on a face-centered cubic array of oxygen atoms with metallic ions distributed in the interstices. These metallic ions were, in part, of the transition metals and octahedrally surrounded by six oxygen atoms.

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Recommendations

Extensive examination of Nb_2O_5 and the niobates should be undertaken to determine if Nb_2O_5 has an even broader use in producing thermoelectric effects in oxide ceramics and to determine if other niobates than those of lead are convertible into thermoelectrics.

High dielectric constant insulators, including titanates, should be tested for thermoelectric effects. Experience indicates that when such materials are converted to semiconductors by doping, the electrical resistivity decreases with increasing temperature. Since the Seebeck coefficient, at least for doped $BaTiO_3$, increases in magnitude with increasing temperature, such materials may be susceptible to further modification to take advantage of both a large Seebeck coefficient and the increased number of carriers which are freed at high temperature. Cadmium niobate is suggested as an example.

An investigation should be initiated of refractory oxides for the development of p-type electronic semiconductors which do not become intrinsic at high temperatures. Co-valent oxides which have properties similar to some of those of SiO_2 should be given first consideration and ionic compounds avoided absolutely.

Separate from thermoelectric phenomena, some of the ionic semiconductors observed in this work should be investigated for use as high temperature solid electrolytes. Li_2TiO_3 is strongly recommended for such consideration and $LaCrO_3$ and $YCrO_3$ are also suggested.

PREPARATION OF MATERIALS

The raw materials for this work, from some of which further compounds and solid solutions were prepared, are listed in Table I; the compound, purity, and source are given. These materials, which include both base materials and "dopants", were used in two ways; as base materials to which "dopants" were added, and to synthesize other compounds to which "dopants were then added. The compounds and solid solutions prepared are listed in Table II. For each preparation, the reactants and conditions of synthesis are given. Additions to base materials were of two orders of magnitude. In a few cases major additions were made; these actually resulted in binary system phases. Minor additions were made in most cases and these were limited to several mol percent of "dopant".

For additions to the base materials, a Standard Series of Additions of dopant was chosen as 0.1, 0.2, 0.5, 1.0, 2.0, 5.0 mol percent. This range of concentrations was selected because it covers the apparent pertinent range of doping for oxides to produce semi-conduction by the controlled valency effect. The increment relation was selected because it is approximately equi-spaced linearly through two decades of the base-10 logarithm scale. When results from an entire Standard Series indicated that other dope levels might produce better thermoelectric effects, then intermediate additions of 3.0 and 4.0 mol percent or extended additions of 4.0, 7.0, and 10.0 mol per cent were prepared.

The uniform procedure devised for preparation of all Standard Series of

Additions was as follows. All materials were weighed on balances sensitive relative to the amount being weighed. The addition for each member of the Series was pre-mixed with a small amount of the base material in a Spex Mixer/Mill for 3 minutes. This pre-mix and the remainder of the base material were then wet blended using water in a laboratory ball mill for one-half hour. The mill discharge was dried at 350°F for 16 hours and then passed through a laboratory Mikropulverizer. For those systems requiring calcination prior to fabrication, the calcination was followed by wet ball-milling to -325 mesh.

FABRICATION OF SHAPES

A Standard Ceramic Body was designed as the test shape for electrical properties. It was desired that this final sintered shape be a right parallelopiped having approximate dimensions of $\frac{1}{4}$" thickness, $\frac{1}{2}$" width, and $2\frac{1}{2}$" length. Thus the ratio of thickness to width to length was 1 to 2 to 10. These shape and dimension conditions were chosen in order to meet requirements for determination of electrical resistivity by the 4-point probe method when all four points of contact are co-planar. To effect this shape, an opposing double-plunger die was designed such that the dimensions of the green body were $2\frac{3}{4}$" by $\frac{7}{10}$" and of variable thickness depending on the particular material. The female die recess was sufficiently deep to accommodate the necessary amount of material, regardless of density, to insure $\frac{1}{4}$" sintered thickness. This entire assembly was mounted on a Blackhawk Porto-Power Press provided with double acting 20 ton hydraulic rams.

The final compositions, as -325 mesh powders, were prepared for forming by the addition of a binder; 5^{w}/o of a solution of 5^{w}/o polyvinyl alcohol in water was used. The powders were loaded into the die and the green bodies were formed by double action at 10,000 psi for 5 seconds. The green bodies were sintered, under their respective varying conditions, in three different kilns. A muffle-type Harper electric kiln with SiC heating elements was used for sinterings up to 2600°F. For temperatures between 2600°F and 3150°F, a gas-fired, down-draft kiln constructed in this laboratory was employed. For those compositions containing metal hydrides, an especially constructed Harper electric kiln with molybdenum elements and atmospheric control of both element and specimen chambers was used to de-hydride the oxide-hydride composites. Insofar as it was possible, optimum conditions of sintering were determined experimentally for each composition. The actual conditions of sintering of each composition are given in the tabulations described below.

The sintered Standard Ceramic Body was electroded at each end of one of the lateral surfaces. This was to insure electrical contact between the material and the external current leads for resistance measurements by the 4-point method. Hanovia No. 6082 platinum paste was applied with a small screed and fired-on by heating to 1500°F with a $\frac{1}{2}$ hour hold time.

EQUIPMENT AND TECHNIQUE OF MEASUREMENT

Ceramic Properties

All ceramic properties were determined from the various weighings, described below, of the Standard Ceramic Body. All weighings were made on a Mettler Type H-15 single pan, precision analytical balance. Distilled water was used as the weighing and saturation media; to insure saturation, all specimens were boiled in water for 2 hours. Each Standard Ceramic Body was weighed dry, saturated, and then suspended. From these weighings were determined absorption, apparent density, bulk density, and porosity; only the latter two characteristics are reported as being the most important. The bulk density was obtained as the quotient of dry weight by the difference between saturated weight and suspended weight. The porosity was obtained from the difference between saturated and dry weights divided by the difference between saturated and suspended weights.

Electrical Properties

Measurement of electrical properties, as a function of temperature to 1250°C, was accomplished with a somewhat elaborate complex of equipment. A horizontal tube furnace, with a Kanthal REH 10-30 1800 watt heating element, was constructed to provide the high temperature environment. The heating element contained a 4" OD zircon tube of $\frac{1}{4}$" wall thickness as a liner; a hot zone of approximately 6" length was obtained within the liner.

A double, parallel position specimen holder of rectangular channel shape, 2" long and $\frac{1}{2}$" inside width, was fabricated of insulating alumina impregnated with alumina cement. A specimen-contact thermocouple (Pt-Pt 10% Rh) was provided at each end of the bottom of each channel, with a non-contact thermocouple (Pt-Pt 10% Rh) in a well adjacent to the "cold" end contact thermocouple. Four point contacts (Pt), linearly spaced $\frac{1}{2}$" apart, were provided in an alumina block which fit inside the channel and rested on top of the specimen. These contacts were for the current leads and "floating voltage" probes.

1. Auxiliary Equipment

Figure I is a schematic diagram of the circuitry for control, switching, and timing of all measurement instrumentation. The timer is set for a period long enough to encompass both the heating and cooling cycles of the furnace, 25°C to 1250°C to 600°C, and the timer contacts closed. This furnishes power to the amplfier and the recorder and closes Relay No. 3. Relay No. 1 is then activated by mechanical pushbutton, turning on the power to the furnace and the Wheelco furnace control. The furnace control then turns on, completing the circuit for the coil of Relay No. 1 and also Relay No. 2. When Relay No. 2 is activated (heating cycle), the circuit for the Automatic Resistance Range Switching Operation (ARRSO) is completed and resistance measurements are made. When the furnace reaches temperature (1250°C), the Wheelco furnace control breaks the circuit for Relays Nos. 1 and 2 shutting off the furnace and Wheelco Control, thus starting the cooling cycle. In the deactivated position Relay No. 2 shuts off the power to the ARRSO and furnishes power to the relays of the Automatic Seebeck Coefficient Measuring Apparatus (ASCMA). At the completion of the

cooling cycle the timer opens the timer contacts, S_1., shutting off the power to the timer motor, amplifier, recorder, and Relay No.3. In the deactivated position, Relay No.3 breaks the power to the ASCMA. Relay No.3 also acts as a fail-safe device in that should the AC power to the recorder fail, the DC power to the ARRSO and ASCMA will be shut off, thus preventing the intermittent duty type relays from burning out if the recorder stops in a position operating the relays.

2. Resistance Measurement; Automatic Resistance Range Switching Operation

Figure II is a schematic diagram of circuitry for the measurement of electrical resistance; the operation is as follows: At recorder points 5 and 6 the recorder closes S_2 operating Relays Nos. 1, 2 and 3. Relay No.1 is a SPST relay connecting the power supply output from R_9 through Relays Nos. 2 and 3 to the specimen current probes. Relay No.2 is a 4PDT latching relay which reverses the polarity of the current to the specimen upon activation. Relay No.3 is a 4PDT relay which, in the activated position on recorder points 5 and 6, connects the current supply to sample 1 and connects the top voltage probes of sample 1, through the reversing Relay No.2, to recorder point 5. In the deactivated position Relay No.2 connects the top voltage probes of sample 2, through reversing Relay No.2, to recorder point 11 and connects the current supply to sample 2. During the 10 sec. print interval of recorder point 5, the following takes place: If the voltage across the specimen is greater than 20 mv, S_3 on the recorder is activated; if S_3 remains closed for longer than the one second time delay afforded by R_1 and C_1 of Relay No.4, Relay No.4 closes and remains closed (due to a holding circuit) shorting out the top voltage probes and precision resistors R_7, R_8, R_9. Thus under the conditions where the specimen has a resistivity of 5 ohm-cm or greater, recorder points 5 and 6 print zero. If, on the other hand, when recorder point 5 comes into print position and S_2 is activated and the drop across the top probes is between 2 mv and 20 mv, then no switches are activated and recorder point 5 records the "floating" voltage representative of true resistance and recorder point 6 records the voltage across the known resistance $R_7+R_8+R_9$.

If the drop across the top voltage probes is less than 2 mv, switch S_4 is activated; if S_4 is closed for one second, Relay No.5 is closed which switches out dropping resistor R_4 and precision resistor R_7. If this increase in current is sufficient to drive the recorder above 2 mv, recorder point 5 prints the top probe voltage as before, and recorder point 6 prints the voltage drop across the known resistance R_8+R_9. If the recorder still remains below 2 mv, Relay No.6 activates one second after Relay No.5, switching out dropping resistor R_6 and precision resistor R_8. Then recorder Point 5 prints the top probe voltage and recorder point 6 prints the voltage drop across precision resistor R_9. Thus there are three approximate current ranges of 2 ma, 15, ma, and 100 ma corresponding to range resistors $(R_7+R_8+R_9$, (R_8+R_9), and R_9 respectively. Now since the top probe voltage and voltage across the appropriate range resistor are known, the exact current can be computed; from the voltage drop, the exact current, and sample dimensions, the resistivity can be computed.

A similar process occurs for recorder point 11 and 12 except that Relays Nos. 2 and 3 are not activated when S_1 is operated for points 11 and 12. Since Relay No. 2 is activated in alternate recorder cycles, the polarity of the current and the consequent polarity of the top voltage probes is reversed for every other recording. Hence it is possible to cancel the Seebeck effect on the resistivity by averaging two successive recordings of the top voltage probes. The time delay circuits are necessary to allow the recorder time to balance in range before switching occurs.

Calculation of resistivity: Consider any given Standard Ceramic Body undergoing two successive measurements, with the indicated current reversal:
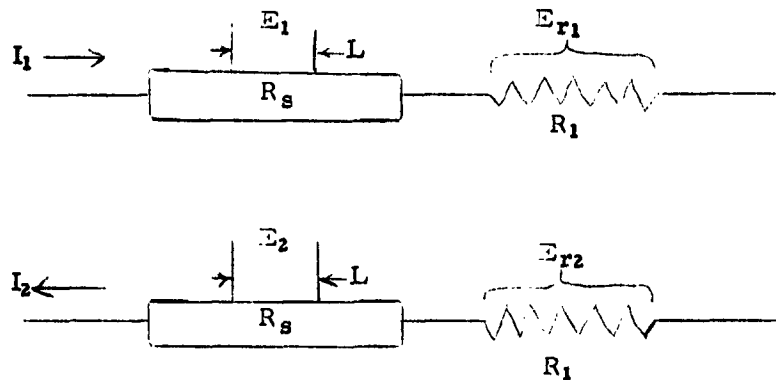
Assume that the Seebeck voltage E_s and the sample resistance R_s remain constant for two successive recorder prints of the top probe voltages E_1 and E_2 and of the voltages E_{r1} and E_{r2} across the precision resistors R_1 and R_2; then

$$E_1 = I_1 R_s + E_s \text{ and } E_2 = I_2 R_s - E_s$$

adding: $$E_1 + E_2 = R_s (I_1 + I_2)$$

but $$I_1 = \frac{E_{r1}}{R_1} \text{ and } I_2 = \frac{E_{r2}}{R_2}$$

substituting $$R_s = \frac{(E_1 + E_2)(R_1 R_2)}{E_{r1} R_2 + E_{r2} R_1}$$

Under most conditions the Seebeck voltage is not large enough to cause a switching of ranges so $R_1 = R_2$ and $E_{r1} \approx E_{r2}$. Hence the equation for sample resistance becomes

$$R_s = \frac{(E_1 + E_2)}{2 E_{r1}} R_1$$

Knowing the resistance $R_{\mathcal{E}}$ for any given sample, the cross sectional area A, and the distance L between the top voltage probes, the resistivity is

$$P_{\mathcal{E}} = \frac{R_s \, A}{L}$$

or

$$P_s = \left[\frac{(E_1 + E_2)\,(R_1\,R_2)}{E_{r_1}\,R_2 + E_{r_2}\,R_1}\right]\left[\frac{A}{L}\right]$$

or

$$P_{\mathcal{E}} = \left[\frac{E_1 + E_2}{2}\right]\left[\frac{R_1}{E_{r_1}}\right]\left[\frac{A}{L}\right]$$

3. Resistance Measurement; Manual Operation

Certain Standard Ceramic Bodies with large Seebeck Coefficients, had resistivities greater than the 5 ohm-cm limit of the ARRSO; the resistance of these specimens were measured manually. The 4-point probe method was employed with the same sample holder and contacts designed for the ARRSO. Four $1\frac{1}{2}$ volt dry cell batteries connected in series furnished the current supply. The measured "floating voltage" was read from a Leeds and Northrup K-2 Potentiometer using a galvanometer to indicate balance. The specimen temperature was read from a Leeds and Northrup portable potentiometer indicator. Figure III shows the circuitry and apparatus used to switch the voltage and current connections from one sample to the other. This switch-gear was also used to reverse the current through the specimen so that the effect of the Seebeck voltage could be eliminated. The resistance was obtained from the voltage drop across the specimen, E_1, and the voltage drop, E_{r_1}, across the known resistor R_1. Then the current was reversed and E_2 and E_{r_2} were obtained. The resistance was calculated as follows:
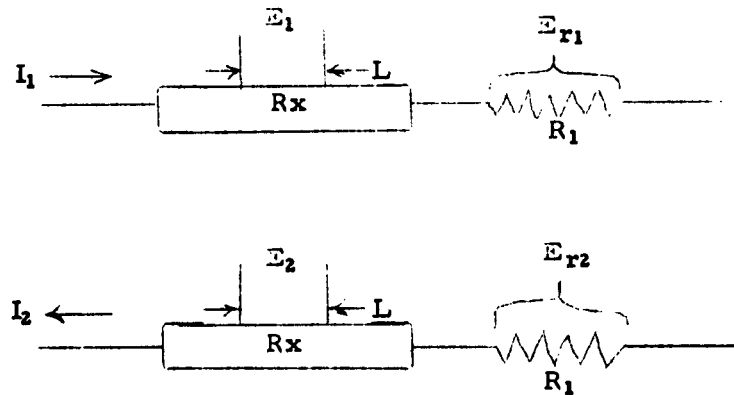
If R_x = resistance of specimen, and

R_1 = resistance of known resistor, then

$$\frac{E_1 + E_2}{R_x} = I_1 + I_2$$

and

$$\frac{E_{r_1} + E_{r_2}}{R_1} = I_1 + I_2 \; ;$$

equating the left-hand-side of these gives

$$R_x = \frac{(E_1 + E_2)\, R_1}{(E_{r_1} + E_{r_2})}$$

and $p = R_x \dfrac{A \text{ (cross section)}}{L \text{ (probe gauge-length)}}$

For each set of data, the furnace was allowed to stabilize at temperature so that E_1 and E_2 were obtained at the same temperature. A specimen-contact thermocouple, shown in Figure III, was used to obtain the temperature of measurement.

4. Seebeck Coefficient Measurement

Figure IV is a schematic diagram of the Automatic Seebeck Coefficient Measuring Apparatus. The temperature, Seebeck voltage, and temperature gradient producing the Seebeck voltage in the two specimens are all recorded with the Leeds and Northrup Speedomax Type G Recording Potentiometer. The recorder prints at 10 sec. intervals and measures 20 mv. full scale.

For sample 1 the temperature is printed at recorder point 1 from the thermocouple not in contact with the sample. Point 2 prints the Seebeck voltage with respect to platinum from the platinum leads of the two thermocouples in contact with the specimen. The Seebeck voltage is fed to the recorder in series with an external +10.0 mv from a Leeds and Northrup potentiometer indicator. This +10.0 mv. effects a center scale zero on the recorder, the recorder then prints both the sign and magnitude of the Seebeck voltage indicating p- and/or n-type semiconduction. At recorder points 3 and 4 Relay No. 1 is energized connecting the thermocouples from sample 1 to Relays Nos. 2 and 3. At recorder point 3 Relay No. 2 is energized connecting the non-contact, or coldest, thermocouple in differential with the cold zone contact thermocouple; this differential output is amplified 100 X and printed. At recorder point 4 the non-contact thermocouple is connected in differential with the hot-zone contact thermocouple; this output is also amplified 100 x and printed. A similar process takes place at recorder points 7, 8, 9 and 10 for sample 2 with Relay No. 1 in the de-energized position. When both Relays Nos. 3 and 4 are in the de-energized position, the input to the amplifier is shorted out giving faster amplifier response at recorder points 3, 4 and 9, 10.

The difference between recorded emfs of say points 3 and 4, divided by the thermoelectric sensitivity of Pt vs Pt-10% Rh at a given temperature, and then divided by 100 gives the temperature gradient in sample 1. Since the Seebeck voltage has been measured and recorded, the Seebeck coefficient can be calculated. The reason for taking the differential emf between the non-contact and contact thermocouples instead of the contact thermocouples directly is that for large Seebeck voltages and low sample resistances, the resistance of leads and relays, connecting both contact thermocouples in differential, may be as large as the sample resistance and hence the Seebeck effect would dominate the differential circuit to the exclusion of the temperature difference.

The following example illustrates how the Seebeck coefficient is obtained from the recorded data. Recorder point 1 was found to read 5.85 mv; 0.15 mv was added to compensate for thermocouple cold junction at room temperature. The temperature for 6.00 mv is 676°C; at this temperature the thermoelectric sensitivity of Pt vs Pt-10% Rh is 0.0103 mv. Dividing 0.0103 mv into 0.079 mv, which was found by taking the difference of potential between recorder points 3 and 4 and dividing by 100, the temperature gradient is found to be 7.7°C. From recorder point 2 the Seebeck emf was found to be -6.45 mv indicating n-type conduction. Dividing -6.45 mv by 7.7°C and multiplying by 1000 gives a Seebeck coefficient of -838μv/°C at 676°C.

5. Thermal Conductivity

Thermal conductivity was approximated using a modified form of the Thermal Conductivity Comparator designed by Kenneth Skinner of the Naval Research Laboratories. The major modification was the addition of circuitry to insure uniform heating cycles. A diagram of this circuitry is shown in Figure V. The Leeds and Northrup Speedomax Type G 4-point Recording Potentiometer was used to measure the "hot" and "cold" temperatures of the specimen; the Brown Electronik Recording Potentiometer was used as a furnace control.

In operation, when the furnace is cold, an opposing voltage is fed in series into the Brown furnace control and adjusted so that this voltage plus furnace thermocouple voltage just equals the voltage needed to drive the furnace control to the pre-set maximum temperature. The clock motor of the programer is then started which decreases the voltage in series with the thermocouple as a linear function of time. The time for a cycle is adjusted by the position of the slide wire before the voltage adjustment. As the opposing voltage decreases, the furnace temperature increases until the thermocouple voltage plus the new opposing voltage shuts off the furnace. This process repeats continually with the furnace increasing in temperature until the opposing voltage is reduced to zero and the thermocouple supplies all the voltage at shut-off temperature. Since the voltage output is approximately a linear function of temperature, the heating cycle is approximately a linear function of time. A linear heating cycle insured reproducibility, whereas a constant input did not.

The results obtained from the Skinner Thermal Comparator are interpreted in the following manner: The Leeds and Northrup Recorder prints two color-coded sets of data for each sample. One set of points represents the temperature of the "hot" side of the specimen and the other set the "cold" side. The temperature gradient in the specimen is obtained by difference, from the raw data, and plotted against the mean temperature. This produces a curve which is a relative indication of the thermal conductivity of the specimen; that is, the smaller the thermal gradient, the higher the thermal conduction. Graphical expression of this relation is shown in Figure VI.

RESULTS

The final data, resulting from measurement of ceramic and electrical properties, are presented either as illustrations or in tables. In both cases the electrical properties are presented as a function of temperature. Electrical properties of the most promising materials, only, are presented graphically; the majority of the results are collected in three tables in an Appendix to this report.

The pertinent ceramic properties of all specimens screened are given in the Appendix; these properties are time and temperature of sintering, bulk density, and porosity. The Seebeck Coefficient and electrical resistivity both at a series of temperatures, and an estimate of the type of conduction mechanism are also given for these materials which are not presented graphically.

Seebeck Coefficients as a function of temperature, for TiO_2 containing several levels of Nb_2O_5, are given in Figure VII; in Figure VIII are given the electrical resistivities as a function of temperature for the same compositions. Figures IX and X show the temperature dependence of Seebeck Coefficient and electrical resistivity, respectively, of TiO_2 containing several levels of Ta_2O_5. The materials presented in these four figures are the best thermoelectrics resulting from this work; all are n-type semiconductors. The most favorable composition is TiO_2 containing $2.0^{m}/o$ Nb_2O_5. This composition has an approximate figure of merit of $7.0 \times 10^{-5}/°C$.

Table AI in the Appendix contains ceramic and electrical results for compositions based on simple oxides: TiO_2, ZrO_2, CeO_2. In Table AII of the Appendix are contained the ceramic and electrical results for those compositions based on lithium metatitanate, Li_2TiO_3, and for the analogous Li_2SnO_3 and $LiAlO_2$. The ceramic and electrical results listed in Table AIII of the Appendix are for compositions based on multiple oxides: $BaTiO_3$, $LaCrO_3$, $YCrO_3$, $PbNb_2O_6$ and $Pb_2Nb_2O_7$.

DISCUSSION

Since thermoelectric energy conversion is essentially an electrical phenomenon, only that aspect of the experimental results are covered here. However, the physical state of a test specimen, as regards conventional ceramic properties, constitutes a prior condition on the resultant electrical properties. Chief amongst these ceramic properties is the porosity of the specimen. Since some Standard Ceramic Bodies were not sintered to zero porosity, the electrical effects of pores should be pointed out. For porosity no greater than a few percent, electrical resistivity increases directly with porosity; at larger porosities, the resistivity of the pore contents enters as that of the second phase of a mixture on a volume basis. The effect of pores on the Seebeck coefficient, that is, the nature of the temperature coefficient of the Fermi level for pores and pore-solid interfaces, is not known.

Observation of Data

The actual recording of the raw electrical data, that is, the instrumental response of the Leeds and Northrup Recording Potentiometer, served as the basis of interpreting analysis of the results. Since neither Hall effect nor diffusion effects were measured, only an estimate could be made, as described below, as to the nature of the conduction mechanism.

The algebraic sign of the Seebeck coefficient, S, was taken as a partial indication of carrier type: for $S > 0$ the net carrier effect was assumed to be due to holes, or direct diffusing cations, or anion vacancies; for $S < 0$ the net carrier effect was assumed to be due to electrons, or direct diffusing anion, or cation vacancies. Two supplementary criteria were available to aid in the estimation of carrier type. A firm, steady print of resistance, by the Leeds and Northrup Recording Potentiometer, was taken to indicate electron or hole conduction; a slow, continuous drift of the resistance print during the 10 record print interval was taken to indicate conduction by ions, either direct or through vacancy mechanism. Alternate high and low print of resistance, upon reversal of direction of external current, was also taken as an indication of ionic conduction, although rectification and thermal gradient effect are both possible explanations of this instrumental response. Combined with drift, this alternation of resistance value was taken as certain indication of ionic conduction; this effect was observed in many materials and was estimated to occur in many other materials, the resistivities of which were too great to respond to instrumental limits. These latter materials are indicated "ionic uncertain" in the tables in the Appendix. However, the thermal gradient and externally applied electric field alternately reinforce and oppose each other, thus confounding the above "uncertainty".

The electrical data alone furnished a criterion of usefulness in that the S^2/p quotient must be equal to or greater than 10^{-5} watt/ cm $(°C)^2$ in order to give $Z = 10^{-3}/°C$. Hence, electrical evaluation determined whether thermal conductivity needed to be measured; none of the materials measured electrically warranted determination of thermal conductivity.

Simple Oxides

Amongst these compositions the only materials that produced a thermoelectric effect were those based on either rutile or fluorite structure; and, indeed, rutile itself is the most favorable material of all those examined. From Figures VII and VIII it is seen that 1.0, 2.0, and $5.0^m/o$ Nb_2O_5 additions to TiO_2 produce moderate thermoelectric semiconductors in the temperature range from 600 to 1200°C; specifically, TiO_2 plus $2.0^m/o$ Nb_2O_5 has a Seebeck coefficient of $-400\mu v/°C$ and 0.1 ohm-cm resistivity. The same levels of additions of Ta_2O_5 to TiO_2, illustrated in Figures IX and X, produce the same results with the important difference that Ta_2O_5 does not lower the resistivity of TiO_2 as much as does Nb_2O_5. All of these compositions are typical n-type, controlled-valency semiconductors with the site-to-site conduction mechanism characteristic of such materials. Since the Seebeck coefficient is the same for Nb_2O_5-doped TiO_2 and Ta_2O_5-doped

TiO_2, then the energy of the electrons in excess of the chemical potential is the same, though the electrical resistivity is different. It should be noted that although stoichiometric imbalance could exist in these compositions, the experimental evidence did not indicate ionic conduction.

It is to be expected that smaller numbers of carriers would mean higher values of Seebeck coefficient and resistivity. Evidence of this is seen in Table AI for the composition TiO_2 plus 0.2^m/o MoO_3:~1100μv/°C and resistivity greater than instrumental limits of 5 ohm-cm. The raw data for this composition are not sufficient, however, to state with certainty that this is an n-type electronic conductor

Amongst fluorite structures, the only noteworthy electronic semiconductor is CeO_2 plus 4^m/o Nb_2O_5:~500μv/°C and 1.5 ohm-cm over the temperature range of 700 to 1200°C, shown in Table AI. This composition is similar to that of TiO_2 doped with Nb_2O_5. Apparent ionic conduction is found in the fluorite structure ZrO_2-7^m/o Y_2O_3 cubic solid solution. Although experimental evidence was not obtained here, it is well established that the conduction mechanism in ZrO_2 is exclusively ionic, via vacancies in the oxygen sublattice. In Table AI it is seen that addition of 10^m/o La_2O_3 to this ZrO_2-based composition resulted in a Seebeck coefficient ranging from +1000μv/°C to +3000μv/°C as the temperature increased from 900 to 1100°C; relaxation of atoms around an anion vacancy results in a net positive charge and hence a positive Seebeck coefficient. Containing 17^m/o sesquioxide, large numbers of oxygen vacancies exist in this composition; the large Seebeck coefficient is attributable to the temperature coefficient of the electrochemical potential of these vacancies. The higher resistivity accompanying the large Seebeck coefficient is expected, but may also be due to small transference numbers for oxygen ions and this in turn to diffusion effects in a thermal gradient and an electric field.

Addition of 10^m/o Nb_2O_5 to ZrO_2-7^m/o Y_2O_3 cubic solid solution, shown in Table AI, produced a Seebeck coefficient of +1000 to +1500μv/°C as the temperature ranged from 800 to 1100°C. Stoichiometrically, this composition is unbalanced in the opposite direction to that discussed above; the Y_2O_3 is more than compensated for by the Nb_2O_5 and the net effect is 3^m/o excess of pentavalent oxide. It was to be expected that the Seebeck coefficient would decrease in magnitude upon stoichiometric compensation, but not that the Seebeck coefficient would remain positive upon over-compensation. It thus appears that the ionic mechanism of conduction in all ZrO_2-based compositions is an intrinsic property of ZrO_2.

Lithium Metatitanate

Of all those Li_2TiO_3-based compositions listed in Table AII, only two are of sufficient consistency of behavior to warrant discussion. Li_2TiO_3 has an MgO-type structure, with a random cation lattice, and undergoes an order-disorder transformation at about 1025°C. The undoped compound appears to be a strong ionic conductor, but the conduction process is quite erratic and is complicated by the order-disorder transformation. The nature of the conduction process may be attributed, in part, to the large difference in charge of the two similar-sized cations. Another contributing factor is a possible metastability of Li_2TiO_3 indicated by the ease of loss of Li_2O through volatilization. Hence, practically all Li_2TiO_3-based compositions exhibited large Seebeck coefficients which varied widely with temperature; either a change in sign or a maximum or minimum occurred. None of these compositions exhibited an electrical resistivity small enough to respond to instrumental limits.

Li_2TiO_3 plus $0.5^m/o$ NiO, Table AII, had a Seebeck coefficient increasing from $+1000\mu v/°C$ at 700°C to $+1500''v/°C$ at 1150°C. A negative Seebeck coefficient should result if the Ni(II) replaces Li (I); but if the Ti(IV) is replaced, a p-type semiconductor should result. Since the cation sublattice is randomly occupied by Li(I) and Ti(IV), and Ni(II) is of the same size as both cations of the host lattice, then both substitutions can occur together. Now the electrical resistivity did not record, so the ionic mechanism of conduction remains uncertain. However, a hole, and/or an electron, contribution to the conduction process may account for the steady, but increasing, value of the Seebeck coefficient over the temperature range of measurement.

Li_2TiO_3 plus $2.0^m/o$ ThO_2 had a Seebeck coefficient decreasing from $-850\mu v/°C$ at 800°C to $-1200\mu v/°C$ at 1225°C. Considered an uncertain electronic conductor, this composition is the only Li_2TiO_3-based material which exhibited a consistent negative Seebeck coefficient. Since Th(IV) is so much larger than the cations of the host lattice, it is difficult to understand how the foreign cation enters the lattice. Also, explanation of the conduction mechanism is not possible with the limited data available.

Multiple Oxides

Structurally, the base compounds of these compositions are all perovskite-like, containing a transition metal ion surrounded by an octohedron of six oxygen atoms. The alignment of these octohedra, however, and their relation to the other cation of the compound, differ in each case. It is significant that the majority of compositions discussed here are apparent ionic conductors.

Barium titanate, a tetragonal perovskite, developed interesting thermo-electric properties when doped with $0.5^m/o$ Nb_2O_5 as shown in Table AIII. Although the resistivity was greater than instrumental limits of 5 ohm-cm, it is rather certain that this composition is an electronic conductor. The Seebeck coefficient ranged from $-1700\mu v/°C$ at 750°C to $-3000\mu v/°C$ at 1225°C, an n-type thermo-electric being produced by substitution of Nb(V) for Ti(IV). The negative sign and increasing magnitude of the Seebeck coefficient indicate that the material is becoming an intrinsic-type semiconductor as the temperature increases. The relatively large Seebeck coefficient may be attributed to two factors. As in the case of TiO_2, the controlled-valency effect is manifest, though the resistivity is not as low. Here, again, the carriers have considerable energy in excess of the chemical potential of the host lattice. The second factor is the large dielectric constant of $BaTiO_3$. When materials which conduct by the site-to-site mechanism are doped at the levels of this composition, the carriers observe the macroscopic dielectric constant of the host rather than the electronic structure of the host lattice. Hence, high dielectric constant insulators are readily modified to semiconductors of substanial Seebeck coefficient by an increase in both dielectric constant and loss factor, the latter ultimately exceeding 100%. Although such a composition has a large number of non-degenerate carriers, the site-to-site conduction mechanism is not effective enough to use such materials for energy conversion.

Lead metaniobate, $PbNb_2O_6$, a ferroelectric with a moderately high dielectric constant, while not a distorted perovskite, does contain discrete NbO_6 octahedra. Addition of $0.5^m/o$ Bi_2O_3 to $PbNb_2O_6$, see Table AIII, resulted in a thermoelectric material somewhat similar to the above $BaTiO_3$ composition. The Seebeck coefficient

ranged from -700 μv/°C at 700°C to -2100 μv/°C at 1100°C with a pronounced minimum of -3300 μv/°C at 1015°C. The electrical resistivity, measured manually under static conditions, dropped from 70,000 ohm-cm at 700°C to 66 ohm-cm at 1200°C, exhibiting the negative temperature coefficient peculiar to oxide ceramic semiconductors.

Since Bi(III) is intermediate in size between Pb(II) and Nb(V), a definite site of substitution cannot be assigned; on the basis of electronegativity, however, Bi(III) should substitute for Pb(II). The thermoelectric semiconduction could arise as a consequence of the same effects ascribed to the BaTiO$_3$ composition above, since both lead and bismuth can exist in other oxidation states. The negative temperature coefficient of both resistivity and Seebeck coefficient indicate that this composition also tends to become an intrinsic semiconductor at high temperature. The decrease in magnitude of the Seebeck coefficient at temperatures above 1015°C might be attributed to the onset of ionic conduction due to thermal agitation since PbNb$_2$O$_6$ melts in the vicinity of 1200°C. It is of interest that just as Nb(V) is effective as a dope in producing thermoelectric semiconductors, so also, a niobate compound can be converted to the same condition by doping.

The orthochromites of some of the Lanthanon elements are perovskite-like compounds, actually having the garnet structure. The compounds, however, do not have the high dielectric constant of ferroelectrics. Compositions based on LaCrO$_3$ and YCrO$_3$ exhibited moderate Seebeck coefficients; all are ionic conductors. The data on the five most noteworthy of these are summarized from Table AIII below.

Composition	Seebeck Coefficient	Electrical Resistivity	Temperature Range	Conduction Mechanism
LaCrO$_3$ + 5.0^m/o TiO$_2$	+500 μv/°C	2-3 ohm-cm	600 to 1100°C	ionic
LaCrO$_3$ + 1.0^m/o ZrO$_2$	+500 to +450	1	600 to 1200	ionic
LaCrO$_3$ + 5.0^m/o SnO$_2$	+575	2	600 to 1200	ionic
YCrO$_3$ + 5.0^m/o TiO$_2$	+850	>5	870 to 1170	ionic, uncertain
YCrO$_3$ + 0.5^m/o ZrO$_2$	+1100	>5	700 to 1200	ionic, uncertain

All compositions based on LaCrO$_3$ and YCrO$_3$ were quite refractory and very difficult to sinter; and not all of them resulted in satisfactory ceramic specimens. In all sintering trials, a dark greenish-grey fume-like deposit was observed on the interior of the sintering container. This indicates vaporization of chromium as some form of oxide. Hence, the stoichiometry of the base compound may be sufficiently out of balance to determine all the observed effects. If sufficient loss of chromium occurred, the number of vacancies in the above compositions may be of the same order of magnitude as in heavily doped ZrO$_2$ discussed before. The description of the observed effects may then be that the Seebeck coefficient is due to the temperature coefficient of the chemical potential of vacancies, the conductivity due to diffusion of ions in the oxygen sublattice via the vacancy mechanism. However, compensation by the added tetravalent oxide very likely occurred.

Referring to the above tabulation, certain general effects are to be noted. Doped $YCrO_3$ and doped $LaCrO_3$ are moderate ionic semiconductors with moderate Seebeck coefficients. A higher Seebeck coefficient and higher resistivity, as a consequence of a smaller number of carriers, are found in $YCrO_3$ than in $LaCrO_3$. The level of doping with tetravalent oxide, does not appear to be too significant, and indeed may not even be necessary. Finally, the orthochromite grouping alone may be the determining factor in the thermoelectric effects noted. These observations, however, depend greatly on the extent of sintering. The orthochromites of yttrium and lanthanum thus appear to be similar to ZrO_2 as regards an inherent ionic conduction process at high temperature.

Positive Seebeck Coefficient Semiconductors

Since all the compositions with positive Seebeck coefficients that are discussed above are ionic conductors, p-type electronic materials should be given separate attention. High temperature p-type semiconduction is virtually impossible to achieve in any material. Experience has shown that the number of thermally energized electrons overwhelms the number of controlled-valency-produced holes with resultant intrinsic semiconduction at high temperature. Numerous examples of this phenomenon are to be found in Tables AI and AIII. Compositions with positive Seebeck coefficients at lower temperatures are seen to undergo considerable change with increasing temperature, the Seebeck coefficient falling through zero to sizeable negative values. Lead metaniobate and lead pyroniobate, each without any addition, are examples of this, as is $PbNb_2O_6$ plus $1.0^m/o$ MoO_3. Other compositions are seen to exhibit a maximum or a minimum in Seebeck coefficient as a function of temperature, some with and some without changing sign. Examples of this behavior are shown by TiO_2 plus $5.0^m/o$ SnO_2, $CeO_2 + 0.2^m/o$ La_2O_3, $Pb_2Nb_2O_7$ plus $1.0^m/o$ Sb_2O_5, and $PbNb_2O_6 + 0.2$ Sb_2O_5. Thus a fundamental characteristic of semiconduction, hindering the development of high temperature p-type thermoelectrics, presents the major obstacle to the production of an efficient thermocouple operating over the temperature range of 700 to 1200°C.

TABLE I

Identification of Raw Materials

Compound	Source			Purity
Antimony (ous) oxide, Sb_2O_3	Fisher Scientific Co.,		A-860	99.7%
Antimony (ic) oxide, Sb_2O_5	"	"	A-857	Technical
Bismuth trioxide, Bi_2O_3	"	"	B-339	99.7%
Chromium(ic) oxide, Cr_2O_3	"	"	B-334	99.4
Ferric oxide, Fe_2O_3	"	"	I-116	99.7
Lead dioxide, PbO_2	"	"	L-101	"Special Micro"
Magnesium oxide, MgO	"	"	M-51	99.8
Molybdic anhydride, MoO_3	"	"	A-174	99.5
Stannic oxide, SnO_2	"	"	T-148	99.4
Stannous oxide, SnO	"	"	T-150	99.9
Thallium (ic) oxide, Tl_2O_3	"	"	T-86	Purified
Tungstic anhydride, WO_3	"	"	A-325	Purified
Lanthanum oxide, La_2O_3	Lindsay Chemical Div. American Potash and Chemical Corp.,		528	99.99%
Neodynium oxide, Nd_2O_3	"	"	629.9	99.9
Thorium oxide, ThO_2	"	"	112	99.9
Cerium oxide, CeO_2	"	"	217	99.9+
Yttrium oxide, Y_2O_3	"	"	1115	99.9
Lithium carbonate, Li_2CO_3	American Potash and Chemical Corp.			Technical
Nickelous oxide, NiO	Baker Chemical Co.,		2796	99.0

TABLE 1 (continued)

Identification of Raw Materials

Compound	Source		Purity
Niobium oxide, Nb_2O_5	Fansteel Metallurgical Co.,	721	99.5
Tantalum oxide, Ta_2O_5	" "	521	99.5
Titanium dioxide, TiO_2	TAM Div., National Lead Co., Vapor Phase		98.4
Zirconium dioxide, ZrO_2	TAM Div., National Lead Co.,	608	99.3
Barium titanate, $BaTiO_3$	TAM Div., National Lead Co.,	510	99.9

TABLE II

Identification of Compounds Prepared

Name of Compound or Solid Solution	Formula	Raw Materials	Synthesis Conditions Temp.	Time
Zirconia-yttria Solid Solution	$Zr_{0.93}Y_{0.07}O_{1.965}$	ZrO_2, Y_2O_3	2300°F	3 hrs
Zirconia-calcia Solid Solution	$Zr_{0.85}Ca_{0.15}O_{1.85}$	ZrO_2, $CaCO_3$	2300	3
Zirconia-ceria Solid Solution	$Zr_{0.83}Ce_{0.17}O_2$	ZrO_2, CeO_2	2300	3
Lithium metatitanate	Li_2TiO_3	Li_2CO_3, TiO_2	1800	3
Lithium Zirconate	Li_2ZrO_3	Li_2CO_3, ZrO_2	2200	2
Lithium aluminate	$LiAlO_2$	Li_2CO_3, Al_2O_3	1700	2
Lithium stannate	Li_2SnO_3	Li_2CO_3, SnO_2	1600	2
Lead metaniobate	$PbNb_2O_6$	$PbCO_3$, Nb_2O_5	1900	3
Lead pyroniobate	$Pb_2Nb_2O_7$	$2PbCO_3$, Nb_2O_5	1900	3
Yttrium orthochromite	$YCrO_3$	Y_2O_3, Cr_2O_3	2300	3
Lanthanum orthochromite	$LaCrO_3$	La_2O_3, Cr_2O_3	2400	3

FIGURE I

AUXILIARY CIRCUITRY FOR ELECTRICAL MEASUREMENTS
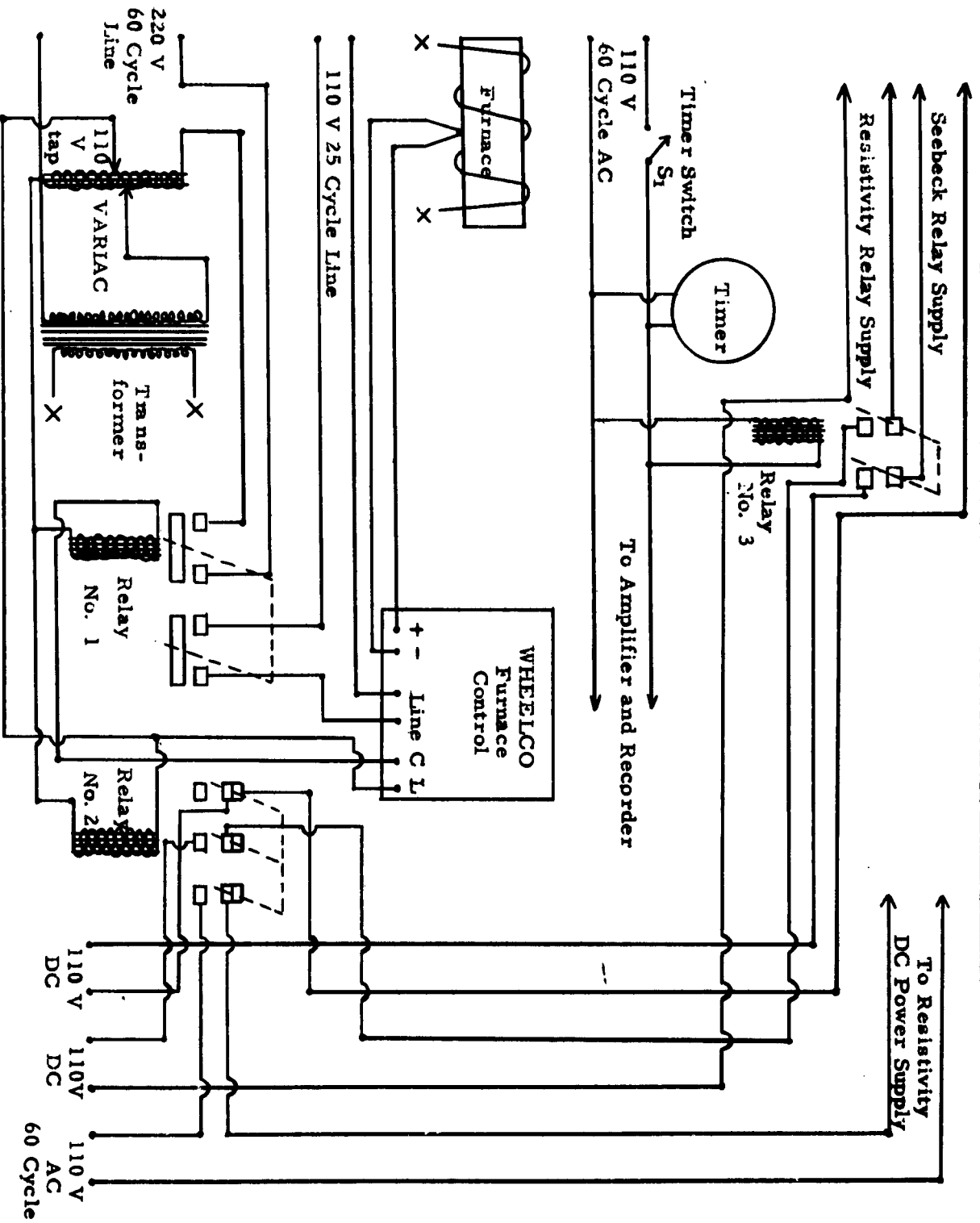
FIGURE II

AUTOMATIC RESISTANCE RANGE SWITCHING OPERATION
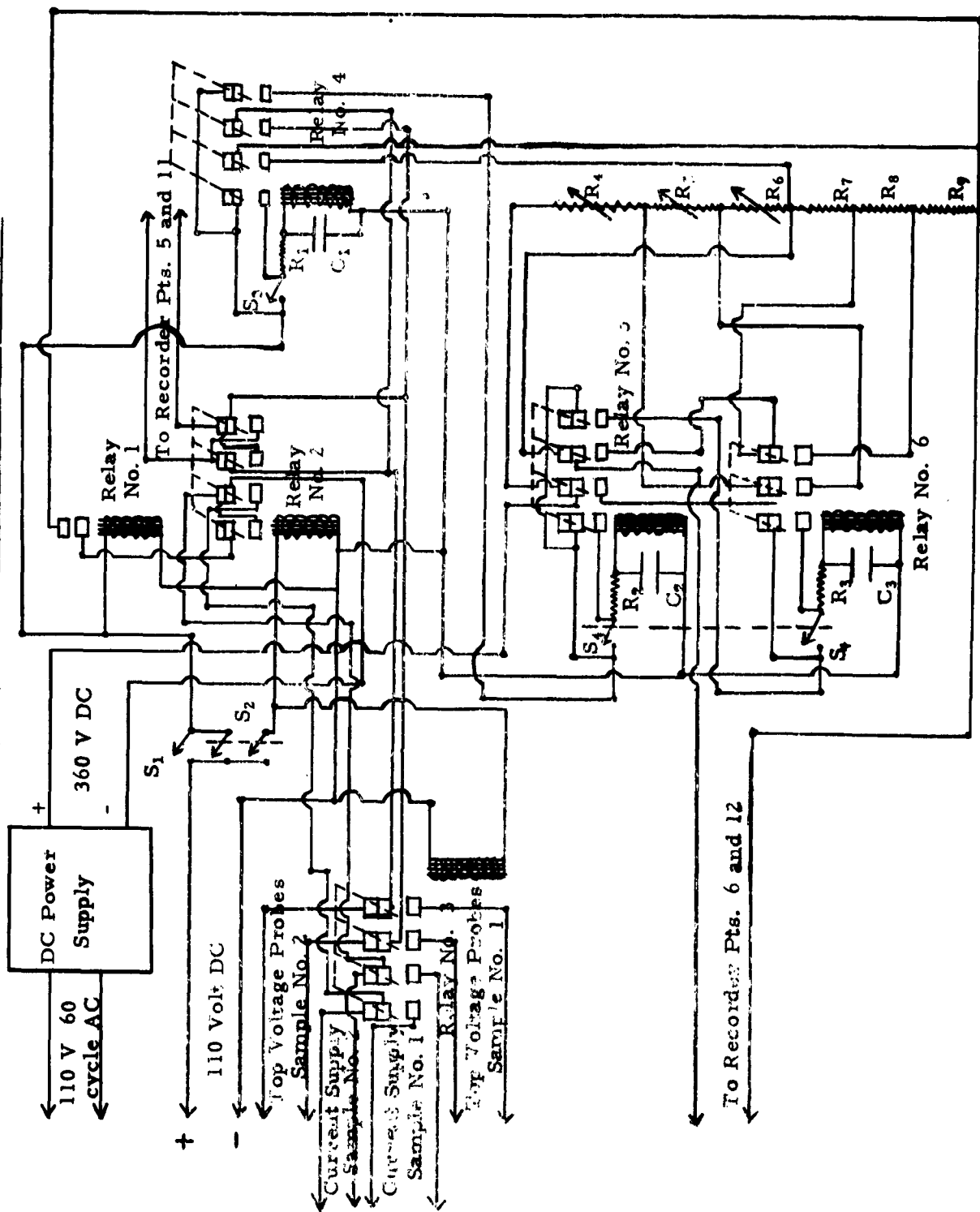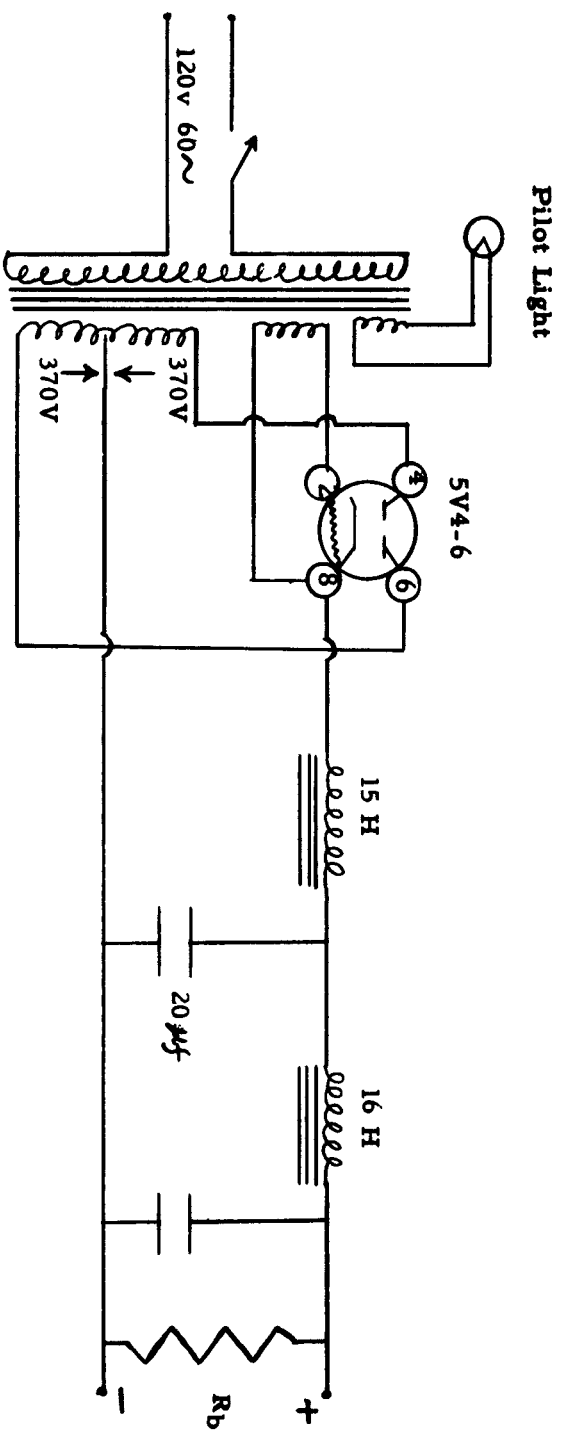
FIGURE II (Supplement)
DC CURRENT SUPPLY
For ARRSO
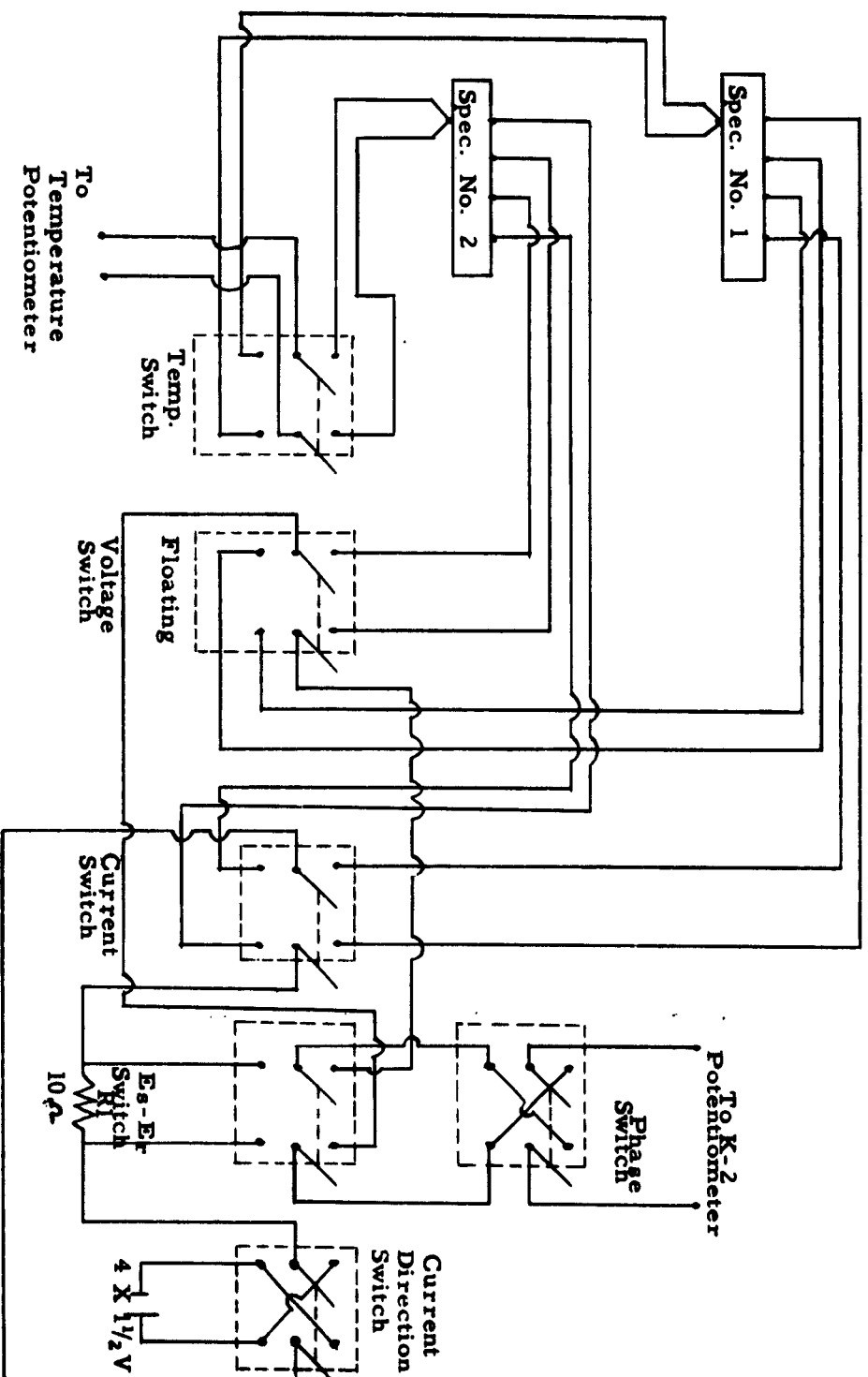
FIGURE III

CIRCUITRY FOR MANUAL MEASUREMENT OF RESISTIVITY

FIGURE IV

AUTOMATIC SEEBECK COEFFICIENT MEASURING APPARATUS
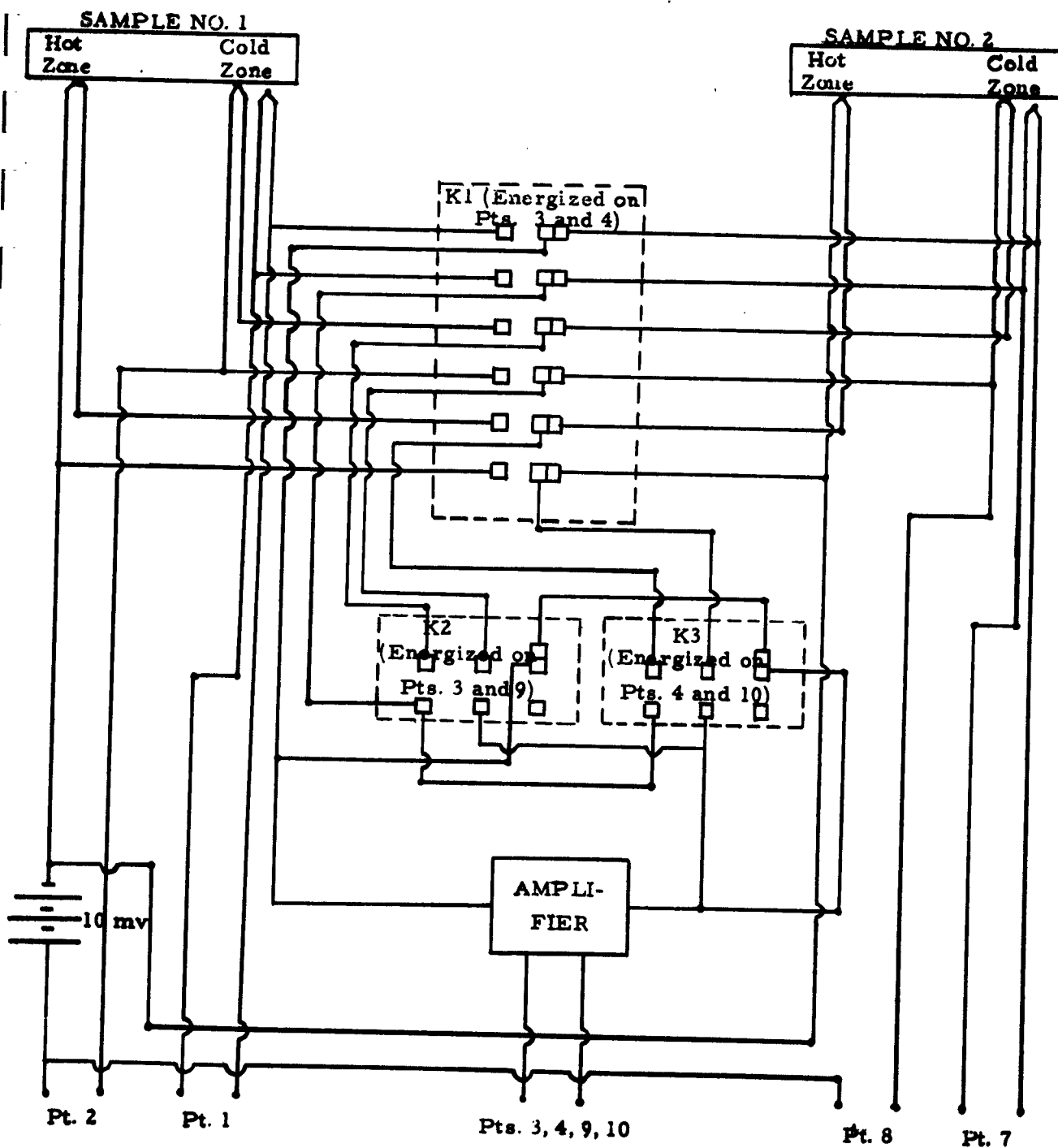
FIGURE V

MODIFIED CIRCUITRY FOR SKINNER THERMAL COMPARATOR

FIGURE VI

TEMPERATURE DIFFERENCE VERSUS MEAN TEMPERATURE SKINNER

THERMAL COMPARATOR, 6 HOUR HEATING CYCLE

□ ZrO₂ (CUBIC ZrO₂-15 ᵐ/o CaO solid solution)

⊙ Al₂O₃ (Pure - Pressed)

△ MgO

⊙ Sapphire
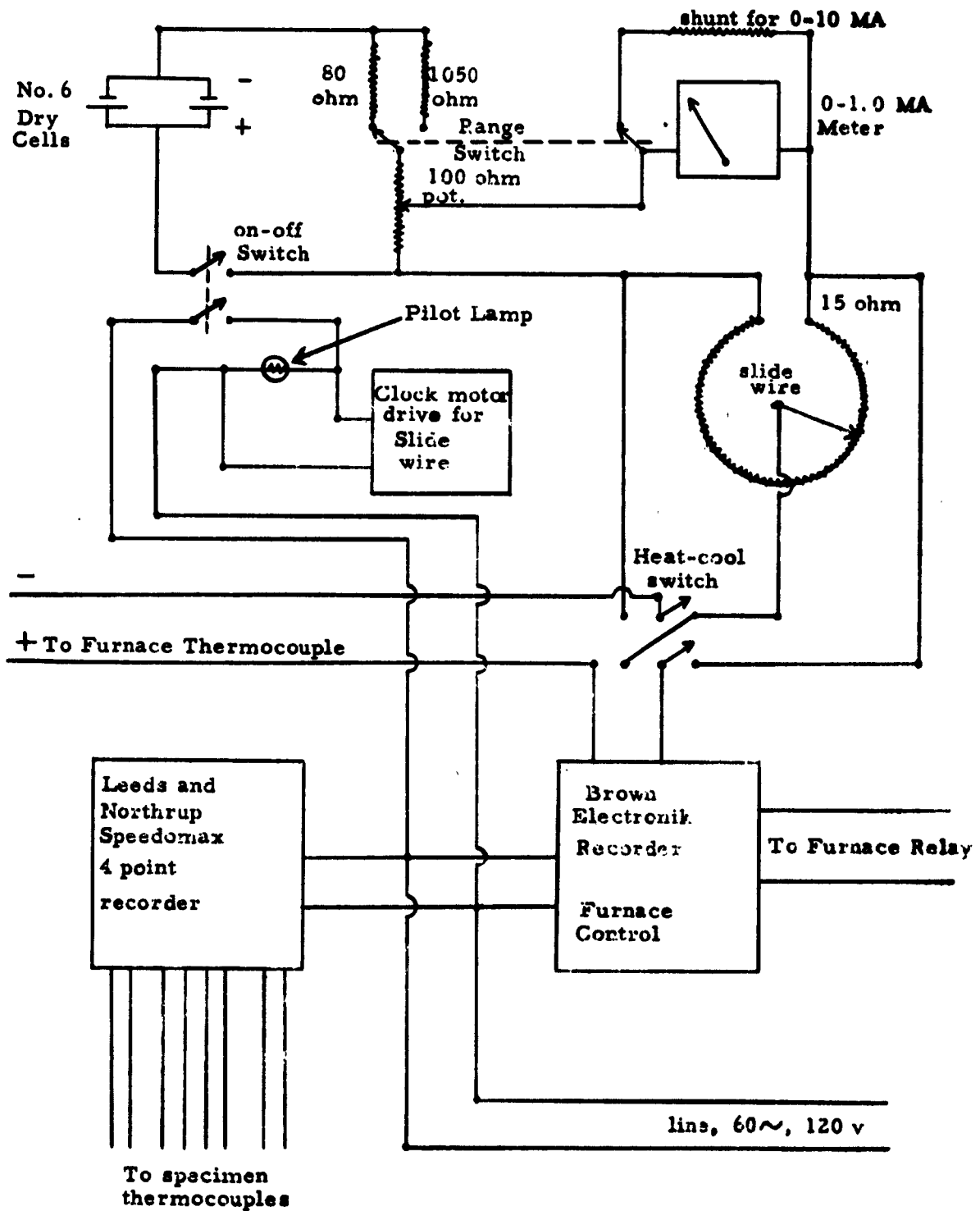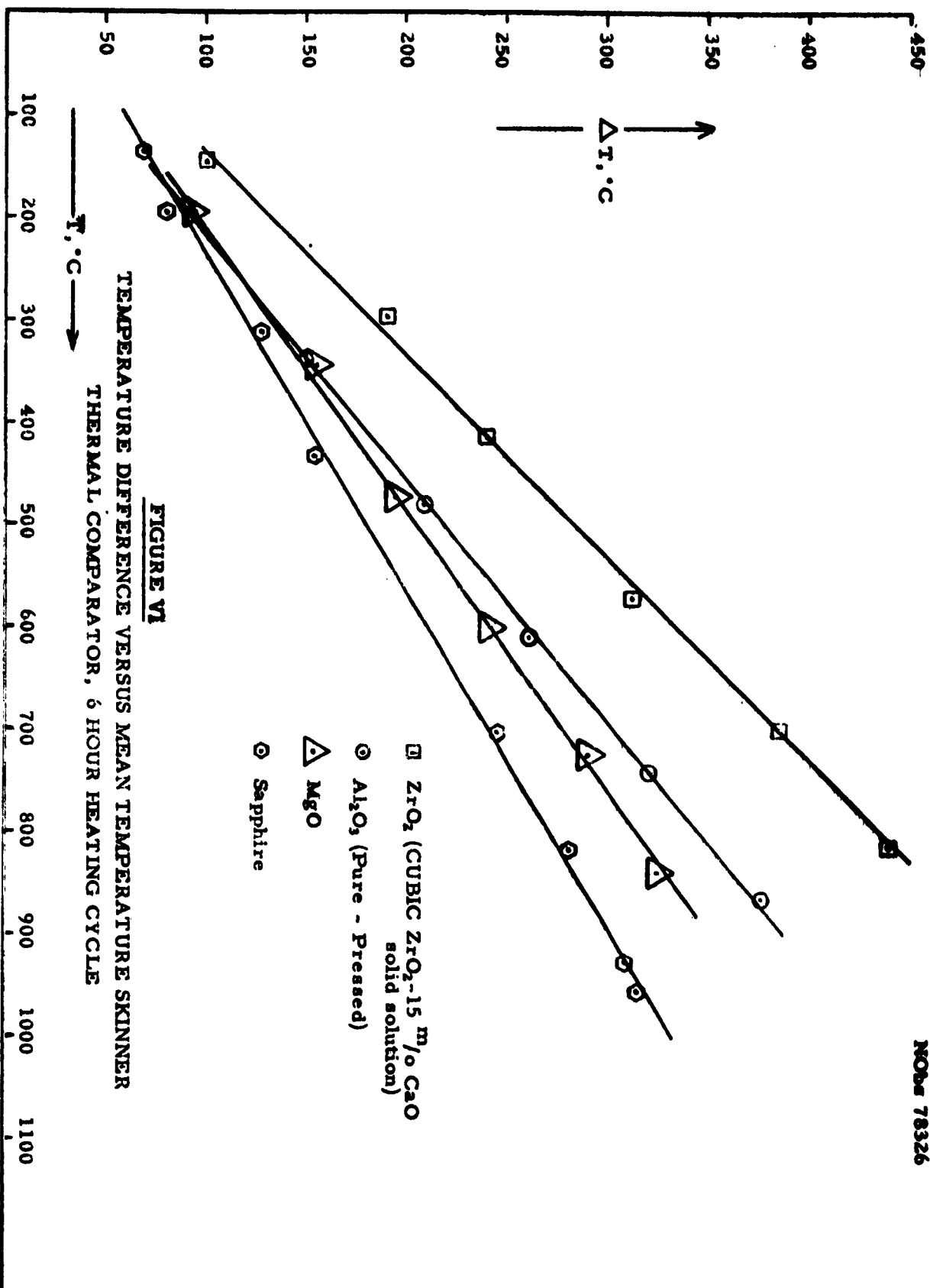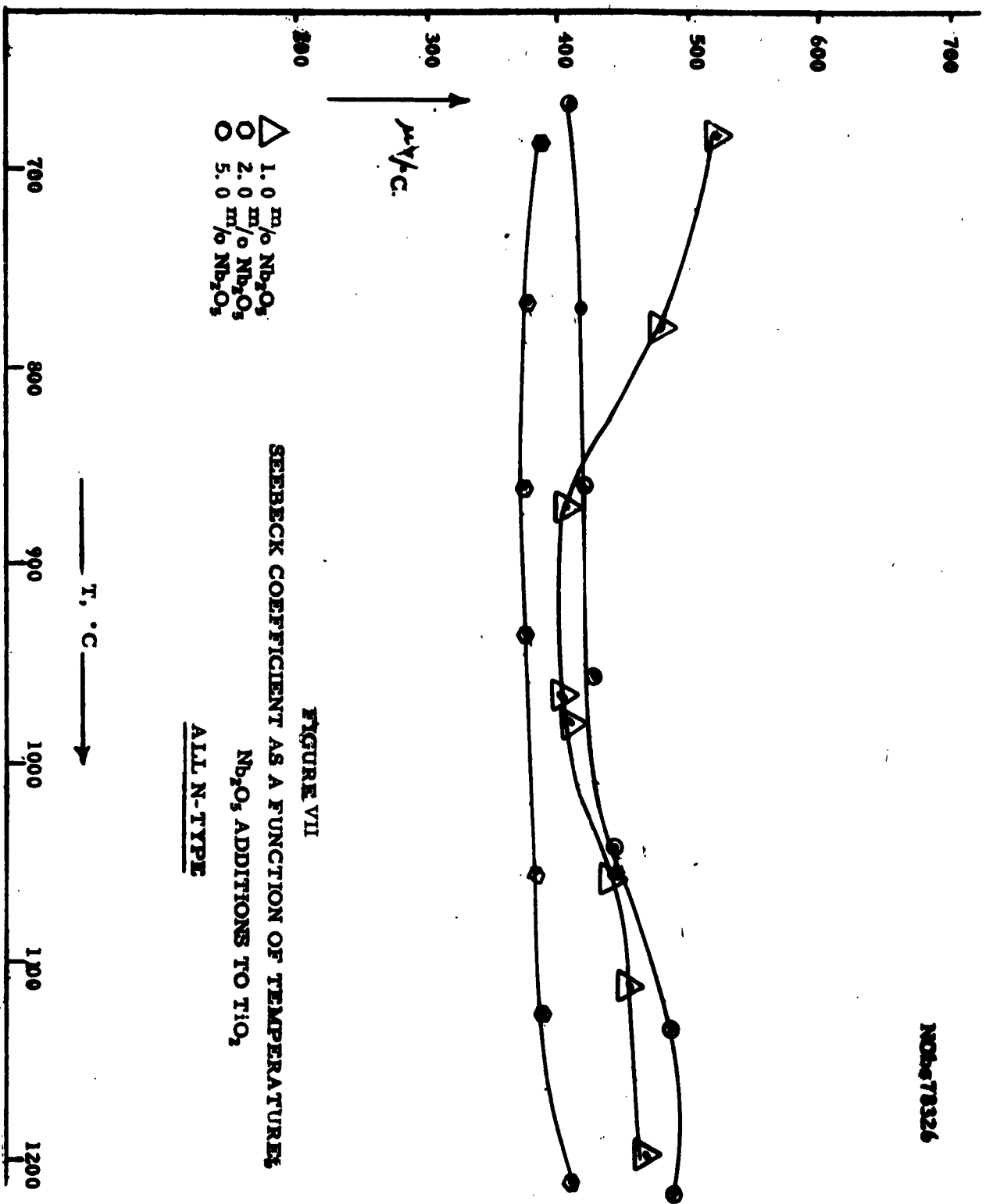
FIGURE VII

SEEBECK COEFFICIENT AS A FUNCTION OF TEMPERATURE,
Nb_2O_5 ADDITIONS TO TiO_2

ALL N-TYPE

△ 1.0 m/o Nb_2O_5
◐ 2.0 m/o Nb_2O_5
○ 5.0 m/o Nb_2O_5

$\mu V/°C$

T, °C

FIGURE VIII

ELECTRICAL RESISTIVITY AS A FUNCTION OF TEMPERATURE
Nb_2O_5 ADDITIONS TO TiO_2
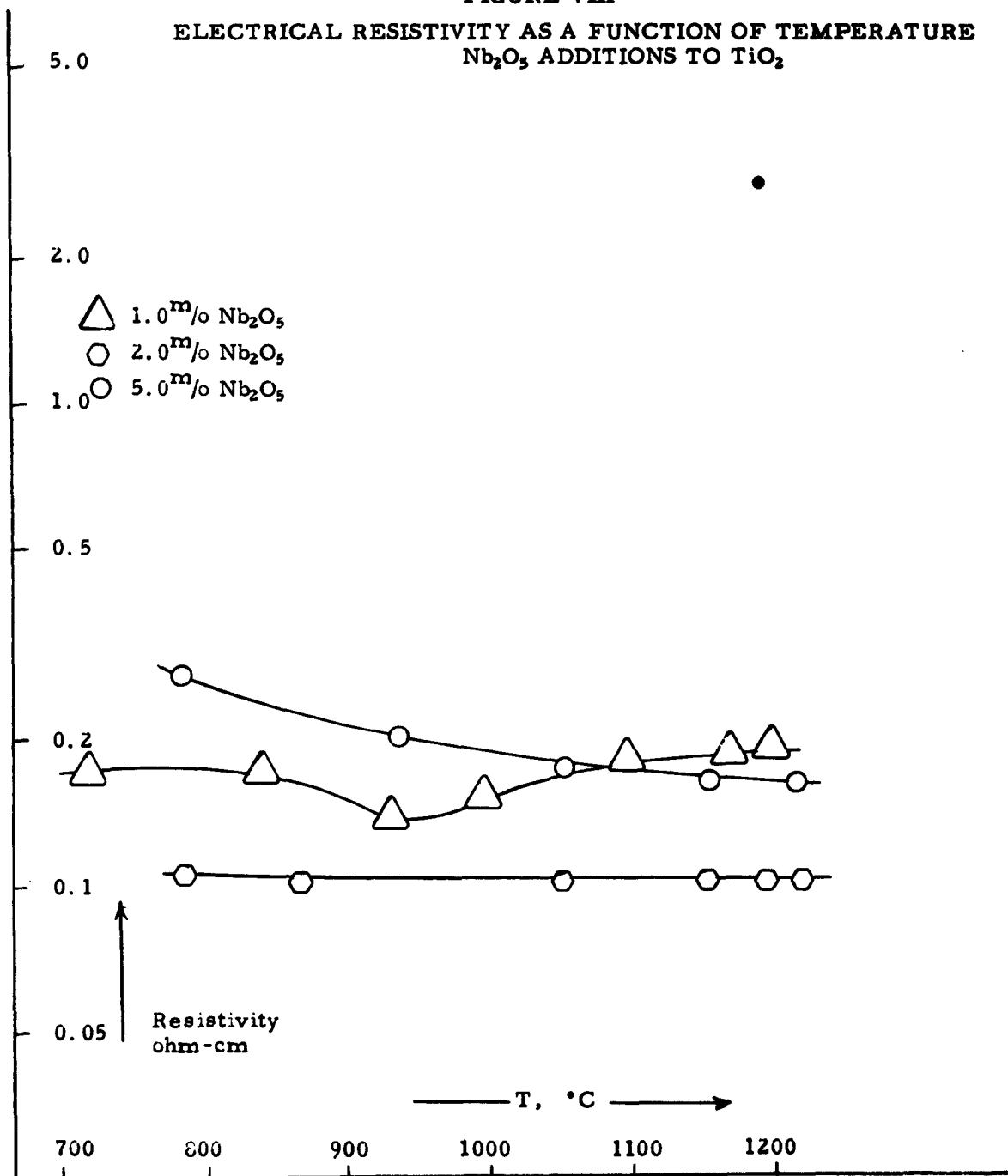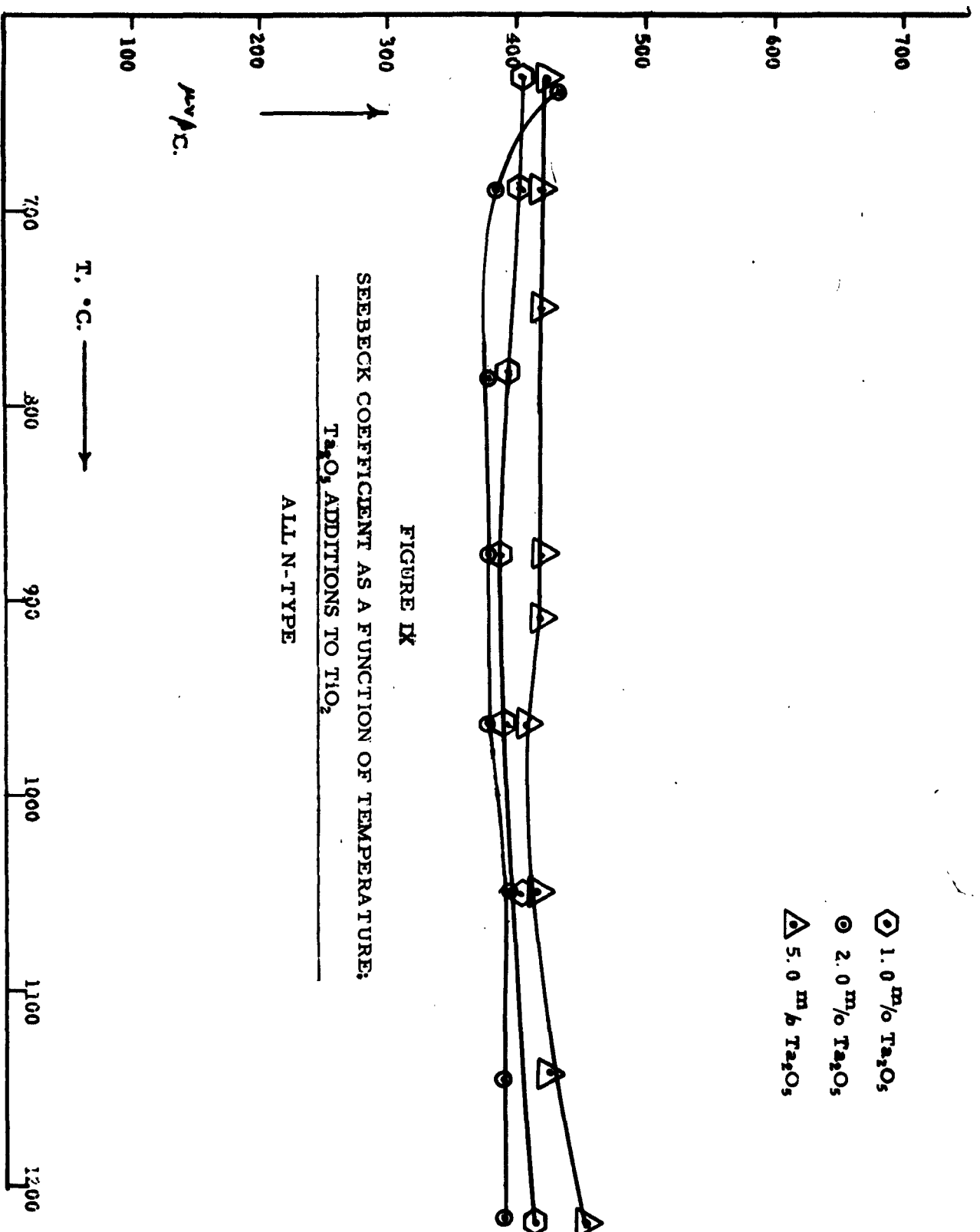
FIGURE IX

SEEBECK COEFFICIENT AS A FUNCTION OF TEMPERATURE:

Ta_2O_5 ADDITIONS TO TiO_2

ALL N-TYPE

FIGURE X

ELECTRICAL RESISTIVITY AS A FUNCTION OF
TEMPERATURE; Ta_2O_3 ADDITIONS TO TiO_2
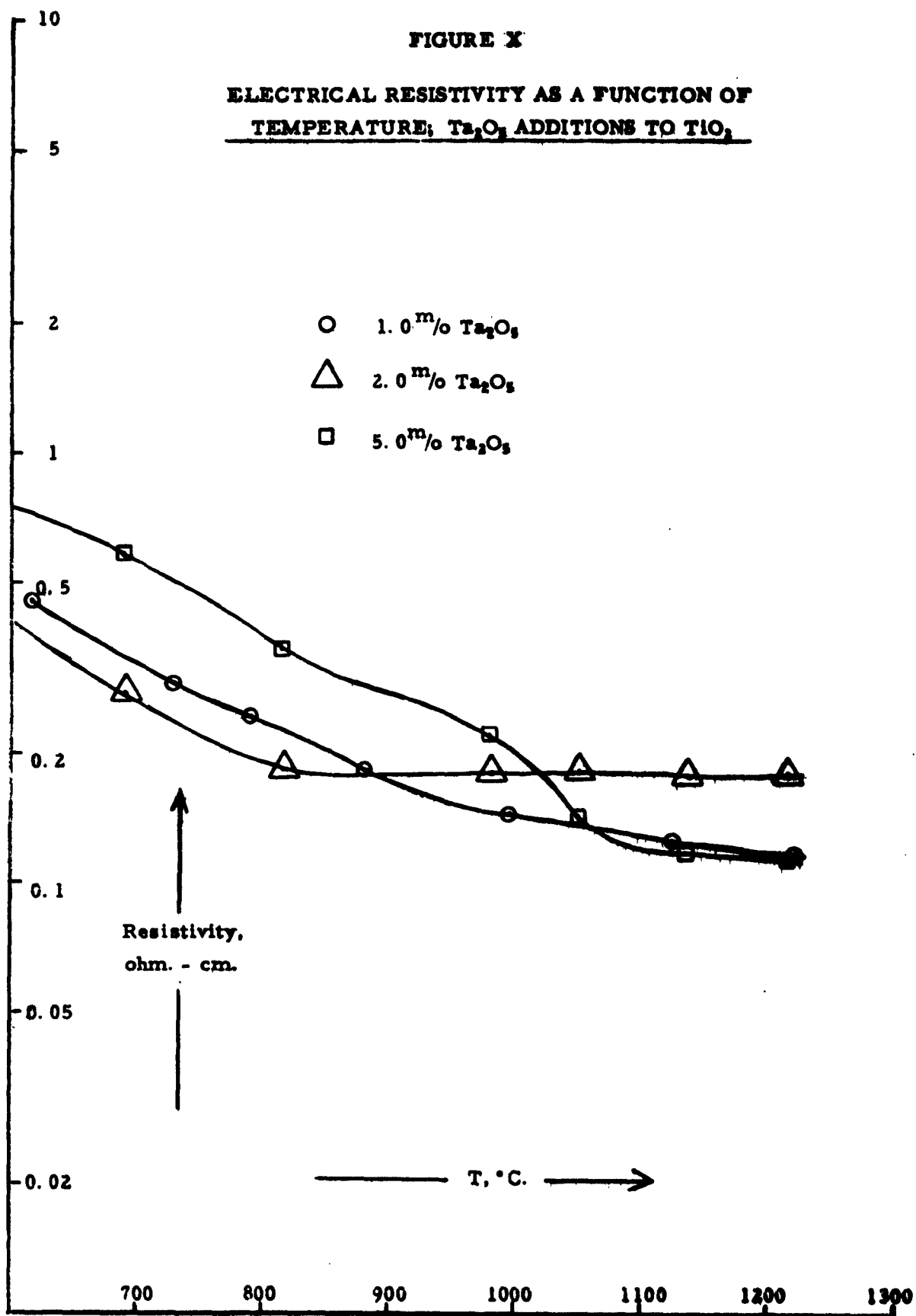
APPENDIX

TABLE AI

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity %	Temperature °C	Seebeck Coefficient μv/°C	Resistivity ohm-cm	Conduction
TiO₂		2600°F	3 hrs	4.05 g/cm³	0.096%	1218 960 852 816	-55 -134 0 +100	>5	electronic uncertain
	0.1 m/o Sb₂O₃	2600°F	3 hrs	4.21	0.000	to 700 870 1054 1200	erratic, +− -550	>5	electronic uncertain
	0.2 m/o Sb₂O₃	2600°F	3 hrs	4.19	0.000	704 870 1182	-457 -435 -370	75	electronic uncertain
	0.5 m/o Sb₂O₃	2600°F	3 hrs	4.17	0.015	690 968 1122 1244	-627 -608 -605 -609	0.74	electronic
	1.0 m/o Sb₂O₃	2600°F	3 hrs	4.12	0.11	690 880 1050 1244	-482 -491 -489 -480	0.26	electronic
	2.0 m/o Sb₂O₃	2600°F	3 hrs	3.57	12.25	732 934 946 1106 1100 1220	-815 -550 -250	2.35 0.78 0.39	electronic
	5.0 m/o Sb₂O₃	2600°F	3 hrs	3.80	9.21	694 906 980 1050 1072 1236	-671 -531 -450	1.12 0.69 0.38	electronic

APPENDIX
TABLE AI (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
TiO_2	0.1 m/o La_2O_3	2400°F	3 hrs	4.39	0.031	874 928 1100 1220	0 +1018 0 -380	>5	electronic uncertain
	0.2 m/o La_2O_3	2400°F	3 hrs	4.42	0.018	1040 1220	0 -550	>5	electronic uncertain
	0.5 m/o La_2O_3	2400°F	3 hrs	4.46	0.028	766 946 1118 1220	0 +605 0 -213	>5	electronic uncertain
	1.0 m/o La_2O_3	2400°F	3 hrs	4.52	0.034	765 829 1050 1220	0 +1680 0 -540	>5	electronic uncertain
	2.0 m/o La_2O_3	2500°F	3 hrs	4.29	0.007	928 1082 1220	+1060 0 -540	>5	electronic uncertain
	5.0 m/o La_2O_3	2600°F	3 hrs	4.45	0.000	820 910 1050 1220	0 +820 0 -400	>5	electronic uncertain
		2600°F	1¾ hrs	4.05	0.000	1218 1054 1038 942	-500 0 +116 +844	>5	electronic uncertain
	0.1 m/o SnO_2	2600°F	1⅔ hrs	4.09	0.000	910 964 1102 1220	0 +266 0 -360	>5	electronic uncertain

A-I

APPENDIX
TABLE AI (continued)
Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	0.2 m/o SnO$_2$	2600°F	1²/₃ hrs	4.03	0.007	964	+565		electronic uncertain
						1050	0		
						1220	-370	>5	
	0.5 m/o SnO$_2$	2600°F	1²/₃ hrs	4.03	0.033	893	0		electronic uncertain
						938	+348		
						1050	0		
						1236	-540	>5	
	1.0 m/o SnO$_2$	2600°F	1²/₃ hrs	4.09	0.016	710	0		electronic uncertain
						928	+930		
						1050	0		
						1220	-425	>5	
	2.0 m/o SnO$_2$	2600°F	1²/₃ hrs	3.98	0.90	820	0		electronic uncertain
						928	+620		
						1033	0		
						1220	-495	>5	
	5.0 m/o SnO$_2$	2600°F	1²/₃ hrs	4.07	0.54	746	-780		electronic uncertain
						765	0		
						910	+910		
						1043	0	>5	
						1220	-500	>5	
		2400°F	3 hrs	3.28	6.49	1224	-484		electronic uncertain
						1118	0		
						976	+583		
						880	+698		
	0.1 m/o LaPO$_4$	2400°F	3 hrs	3.70	2.48	722	-692		electronic uncertain
						-836	0		
						880	+200		
						1050	0		
						1220	-557	>5	

APPENDIX
TABLE AI (continued)
Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
TiO$_2$	0.2 ^{m}/o LaPO$_4$	2400°F	3 hrs	3.92	5.93	600 to 695 914 1156 1220	erratic, neg. 0 +1253 0 -166	>5	electronic uncertain
	0.5 ^{m}/o LaPO$_4$	2400°F	3 hrs	3.77	7.60	700 to 880 1080 1200	erratic, neg. +1084 0 -410	>5	electronic uncertain
	1.0 ^{m}/o LaPO$_4$	2400°F	3 hrs	3.80	0.161	770 906 954 994 1200	-1149 0 +55 0 -532	>5	electronic uncertain
	2.0 ^{m}/o LaPO$_4$	2400°F	3 hrs	3.47	17.41	600 to 685 825 1054 1220	erratic, neg. 0 +565 0 -366	>5	electronic uncertain
	5.0 ^{m}/o LaPO$_4$	2450°F	3 hrs	3.65	13.99	<825 825	erratic, ± +571	>5	electronic uncertain
	0.1 Nb$_2$O$_5$	2400°F	3 hrs	3.76	2.71	700 to 880 994 1114	erratic +400 0 -450	>5	electronic uncertain
	0.2 Nb$_2$O$_5$	2400°F	3 hrs	3.55	1.84	700 to 880 994 1114	erratic, neg +280 0 -485	>5	electronic uncertain

APPENDIX
TABLE AI (continued)
Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
TiO₂	0.5 Nb₂O₅	2400°F	3 hrs	3.55	1.49	to 700 896 978 1208	erratic, neg -606 -450 -880	> 5	electronic uncertain
	1.0 Nb₂O₅ 2.0 Nb₂O₅ 5.0 Nb₂O₅	2400°F 2400°F 2400°F	3 hrs 3 hrs 3 hrs	3.51 3.73 3.93	18.2 } 9.29 } 4.49 }	See Figures VII, VIII			
		2600°F	3 hrs	4.15	0.000	1232 1206 1046 888	-264 0 +1488 +1640	>5	electronic uncertain
	0.1 ᵐ/o Ta₂O₅	2600°F	3 hrs	4.03	0.000	914 1020 1208	+912 0 -648	>5	electronic uncertain
	0.2 ᵐ/o Ta₂O₅	2600°F	3 hrs	3.93	2.47	914 950 1208	+505 0 -653	>5	electronic uncertain
	0.5 ᵐ/o Ta₂O₅	2600°F	3 hrs	3.76	8.87	<880 880 1200	large erratic, neg.	>5	electronic uncertain
	1.0 ᵐ/o Ta₂O₅ 2.0 ᵐ/o Ta₂O₅ 5.0 ᵐ/o Ta₂O₅	2600°F 2600°F 2600°F	3 hrs 3 hrs 3 hrs	4.27 4.50 4.52	0.000) 0.000) 1.65)	See Figures, IX, X			
	0.1 MgO₃	2400°F	3 hrs	4.14	0.29	1206 <1206	-1000 very erratic	>5	electronic uncertain
	0.2 MgO₃	2400°F	3 hrs	3.87	4.65	732 870 968 1224	-1150 -1170 -1170 -1070	>5	electronic uncertain

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APPENDIX
TABLE AI (continued)
Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	0.5 MoO₃	2400°F	3 hrs	3.82	8.27	732 870 985 1219	-830 -820 -1110 -830		electronic uncertain
	1.0 MoO₃	2500°F	3 hrs	3.96	0.052	802 932 1038 1140	-988 -1093 -1000 -1086	>5	electronic uncertain
	2.0 MoO₃	2600°F	3 hrs	3.98	0.000	1206 <1200	-750 very large neg.	7.8	electronic uncertain
	5.0 MoO₃	2600°F	3 hrs	4.10	0.000	770 >770	-927 erratic, neg	>5	electronic uncertain
ZrO₂-15 m/o CaO Solid Solution		3000°F	2 hrs	4.52	17.50	680 857 950 1080 1230	-584 -565 -529 -313 -161	>5	ionic, uncertain
	0.1 m/o Nb₂O₃	3000°F	2 hrs	4.58	17.36	750 760 880 1240	-458 -170 +820 +508	4.45	ionic
	0.2 m/o Nb₂O₃	3000°F	2 hrs	4.59	15.08	732 780 890 1230	-525 0 +1050 +485	4.4	ionic
	0.5 m/o Nb₂O₃	3000°F	2 hrs	4.57	16.57	840 890 1230	-530 +1000 +544	4.58	ionic

TABLE AI (continued)
Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	1.0 m/o Nb₂O₅	3000°F	2 hrs	4.68	15.29	656 732 825 1230	-450 -120 +1140 +470	3.48	ionic
	2.0 m/o Nb₂O₅	3000°F	2 hrs	4.88	1.73	656 732 825 1230	-1240 -79 +1560 +490	>5	ionic uncertain
	5.0 m/o Nb₂O₅	3000°F	2 hrs	5.05	7.97	610 742 960 1230	-1060 -178 +1370 +1010	>5	ionic uncertain
	0.1 m/o La₂O₃	3000°F	2 hrs	4.60 g/cm³	15.56	722 788 840 942 1200	-306 -67 +750 +666	4.78	ionic
	0.2 m/o La₂O₃	3000°F	2 hrs	4.58	15.51	722 840 870 1218	-454 -38 +811 +505	5.56	ionic
	0.5 m/o La₂O₃	3000°F	2 hrs	4.59	15.77	788 906 1050 1208	erratic, ± +1542 +700 +528	5.2	ionic
	1.0 m/o La₂O₃	3000°F	2 hrs	4.58	16.51	840 850 906 990 1200	-1124 -54 +978 +578	5.5	ionic

APPENDIX
TABLE AI (continued)
Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
ZrO_2-7m/o Y_2O_3 Solid Solution	2.0 m/o La_2O_3	3000°F	2 hrs	4.66	16.04	650 728 1190	-323 -29 +554	5.65	ionic
	5.0 m/o La_2O_3	3000°F	2 hrs	4.32	20.39	656 765 980	-610 -32 +560	>5	ionic uncertain
	0.1 m/o La_2O_3	3000°F	2 hrs	4.86	15.28	760 860 964 1100 1206	+1106 +1901 +641 +866 +695	4.03 ohm-cm	ionic
	0.2 m/o La_2O_3	3000°F	2 hrs	4.85	15.15	964 1020 1100 1140 1206	-3333 -3040 -1264 -13 +181	4.5	ionic
	0.5 m/o La_2O_3	3000°F	2 hrs	4.92	14.85	856 892 1000 1080 1156	-1290 0 +490 +516 +521	>5	ionic
	1.0 m/o La_2O_3	3000°F	2 hrs	4.96	14.52	820 856 892 1000 1156	+1315 +961 +690 +590 +544	>5	ionic uncertain
	2.0 m/o La_2O_3	3000°F	2 hrs	5.14	12.91	806 834 860 960 1198	-1164 -11 +324 +465 +550	4.65	ionic

APPENDIX
TABLE AI (continued)
Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	5.0 m/o La$_2$O$_3$	3000°F	2 hrs	5.09	9.54	834 860 960 1200	+816 +910 +582	4.17	ionic
	4 m/o La$_2$O$_3$	3000°F	2 hrs	5.24	7.0	<843 924 950 1140	erratic, neg 0 +1410 >+1720	> 5	ionic uncertain
	7 m/o La$_2$O$_3$	3000°F	2 hrs	5.33	3.8	870 950 1046 1122	>+2000 +861 +1500 +2700	>5	ionic uncertain
	10 m/o La$_2$O$_3$	3000°F	2 hrs	5.55	0.6	<797 906 994 1097	erratic, neg +1000 +1180 +3070	>5	ionic uncertain
	0.1 m/o Nb$_2$O$_5$	3000°F	2 hrs	4.96 g/cm^3	12.36	792°C to 920 1210	0·1V/°C +1769 +914	>5	ionic uncertain
	0.2 m/o Nb$_2$O$_5$	3000°F	2 hrs	4.99	11.51	900 946 982 1016 1210	erratic, pos 0 -84 0 +38	>5	ionic uncertain
	0.5 m/o Nb$_2$O$_5$	3000°F	2 hrs	5.00	11.92	650 784 1220	0 +1209 +427	>5	ionic uncertain
	1.0 m/o Nb$_2$O$_5$	3000°F	2 hrs	5.03	11.26	837 856 1220	0 +1117 +736	>5	ionic uncertain

TABLE AI (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	2.0 m/o Nb$_2$O$_5$	3000°F	2 hrs	5.21	7.38	838 874 1220	0 +700 +1095	 >5	ionic uncertain
	5.0 m/o Nb$_2$O$_5$	3000°F	2 hrs	5.46	0.013	750 788 <800 811 898 978 998 1080 1170 1200 1220	- - erratic, neg 0 - - > +2300 - - - +213	2962 2030 - - 766 420 - 187 111 97.7	ionic
	4.0 m/o Nb$_2$O$_5$	3000°F	2 hrs	5.60	0.013	<986 986 1038 1156	erratic, pos 0 -950 > |-147|	1.78	electronic ionic
	7.0 m/o Nb$_2$O$_5$	3000°F	2 hrs	4.85	14.7	<924 924 950 1097	erratic, neg 0 +355 > +1785	 >5	ionic uncertain
	10.0 m/o Nb$_2$O$_5$	3000°F	2 hrs	4.97	13.4	<770 770 825 880 1002 1140	erratic, neg 0 +1064 > +1176 > +1538 > +1612	 >5	ionic uncertain

APPENDIX
TABLE AI (continued)
Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
ZrO_2 17% CeO_2 Solid Solution	0.1 m/o La_2O_3	3000°F	2 hrs	5.70	3.61	722 770 890 1240	-1106 0 +3225 +9000	>5	ionic uncertain
	0.2 m/o La_2O_3	3000°F	2 hrs	5.56	4.99	erratic results thru out			unknown
	0.5 m/o La_2O_3	3000°F	2 hrs	5.69	3.26	790 924 1250	0 +2044 +630	>5	ionic uncertain
	1.0 m/o La_2O_3	3000°F	2 hrs	5.64	3.57	915 1250	+639 +664	>5	ionic uncertain
	2.0 m/o La_2O_3	3000°F	2 hrs	5.44	3.81	915 1250	+2631 +630	>5	ionic uncertain
	5.0 m/o La_2O_3	3000°F	2 hrs	5.47	4.06	860 1250	+1470 +370	>5	ionic uncertain
	0.1 m/o Nb_2O_5	3000°F	2 hrs	5.58	3.58	798 968 1093 1190	-213 >+3600 +1153 -1800	>5	ionic uncertain
	0.2 m/o Nb_2O_5	3000°F	2 hrs	5.52	4.08	<1100 1118 1182	very large neg -3800 -1300	>5	electronic uncertain
	0.5 m/o Nb_2O_5	3000°F	2 hrs	5.60	4.37	<732 852 976 1114	erratic, neg >-787 >-877 >-1000	>5	electronic uncertain
	1.0 m/o Nb_2O_5	3000°F	2 hrs	5.42	8.2	906 1034 1150 1223	-589 -882 -833 -545	>5	electronic uncertain

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TABLE AI (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions		Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
		Temp.	Time						
	2.0 m/o Nb_2O_5	Failed							
	5.0 m/o Nb_2O_5	Failed							

Base Material	Addition	Sintering Conditions			Shrinkage	Temp. °C	Seebeck Coefficient	Resistance
		Temp.	Time	Atmosphere				
ZrO_2	55 m/o $ZrH_{1.33}$	2200°F	4 hrs	argon	8.85%	784 / 960 / 1140 / 1219	erratic, ΔT too large	0.008 ohms / 0.012 / 0.011 / 0.007
	50 m/o $ZrH_{1.33}$	2200°F	4 hrs	argon	9.10	646 / 714 / 806 / 875 / 1050 / 1219	+12.7 / +16.4 / +11.4	0.021 / 0.017 / 0.020 / 0.013
	45 m/o $ZrH_{1.33}$	2200°F	4 hrs	argon	9.60	1218	unreliable specimen oxidized	0.006
	40 m/o $ZrH_{1.33}$	2200°F	4 hrs	argon	9.60		specimen oxidized	

TABLE AI (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient erratic, + −	Resistivity	Conduction
CeO$_2$		3000°F	2 hrs	6.56	0	<814	erratic, + −	>5.00	uncertain
						814	0		
						850	+431		
						938	0		
						1086	-489		
						1220	-575		
	0.1^{m}/o Nb$_2$O$_5$	2900°F	2 hrs	7.14	28.17	596	-780		electronic uncertain
						692	-786		
						878	-796		
						1054	-729		
						1214	-669		
	0.2^{m}/o Nb$_2$O$_5$	2900°F	2 hrs	6.98	17.59	694	-700	~5	electronic uncertain
						878	-760		
						1010	-615		
						1205	-710		
	0.5^{m}/o Nb$_2$O$_5$	2900°F	2 hrs	5.87	16.57	606	-625	>5	electronic
						786	-604		
						931	-647		
						1205	-717		
	1.0^{m}/o Nb$_2$O$_5$	2900°F	2 hrs	5.90	14.82	596	-625	3.05	electronic
						786	-588		
						913	-587		
						1188	-595		
	2.0^{m}/o Nb$_2$O$_5$	2900°F	2 hrs	5.98	10.66	596	-457	1.66	electronic
						692	-456		
						878	-496		
						1054	-504		
						1088		1.24	
						1214	<-527	0.73	

TABLE AI (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	5.0 m/o Nb_2O_3	2900°F	2 hrs	6.10	1.69	616	-455		electronic
						730	-450		
						817	-433		
						958	-466		
						1153		1.13	
						1205	-482		
	3 m/o Nb_2O_3	3000°F	2 hrs	6.07	1.40	728	-450		electronic
						760		5.05	
						806	-438		
						950		1.55	
						960	-424		
						1050		0.90	
						1097	-500		
						1173		0.69	
	4.0 m/o Nb_2O_3	2900°F	2 hrs	5.79	5.42	732	-515		electronic
						806	-504		
						880	-512		
						986		1.56	
						1004	-523		
						1080		1.32	
						1120	-522		
						1198		1.13	
CeO_2	0.1 m/o La_2O_3	2900°F	2 hrs	5.88	16.85	740	0		mixed uncertain
						795	+3		
						859	0		
						904	+188	>5	
						1013	0		
						1053	-129		
						1220	-529		

APPENDIX

TABLE AI (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	0.2 m/o La_2O_3	2900°F	2 hrs	4.90	16.21	740	-800		
						805	0		
						878	+940		
						940	+614		
						1112	0		
						1172	-277	>5	mixed uncertain
	0.5 m/o La_2O_3	2900°F	2 hrs	6.25	8.47	654	-120		
						692	-416		
						786	0		
						823	+168		
						913	+412		
						1019	+427		
						1171	0		
						1208	>|-109|	>5	mixed uncertain
	1.0 m/o La_2O_3	2900°F	2 hrs	5.86	17.66	692	-189		
						823	0		
						913	+374		
						1035	+311		
						1188	0		
						1208	-30	>5	mixed uncertain
	2.0 m/o La_2O_3	2900°F	2 hrs	5.62	24.39	832	0		
						841	+303		
						1101	+386		
						1104	+333		
						1238	<|+159|	>5	mixed uncertain
	5.0 m/o La_2O_3	2900°F	2 hrs	4.80	46.38	832	0		
						841	+466		
						1101	+423		
						1104	+584		
						1238	<|+691|	>5	ionic uncertain

APPENDIX

TABLE AI (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
CeO_2	0.1 m/o Y_2O_3	2900°F	2 hrs	6.01	12.59	694	-361		mixed uncertain
						820	0		
						860	+281		
						1018	+143		
						1053	0		
						1250	<|-510|	>5	
	0.2 m/o Y_2O_3	2900°F	2 hrs	6.10	9.30	<692	erratic+		mixed uncertain
						692	0		
						730	-302		
						841	0		
						966	+382		
						1138	0		
						1170	-119		
						1220	<|-262|	>5	
	0.5 m/o Y_2O_3	2900°F	2 hrs	6.38	2.47	<823	erratic+		ionic uncertain
						823	+194		
						860	+276		
						966	+277		
						1120	+217	>5	
	1.0 m/o Y_2O_3	2900°F	2 hrs	6.29	5.38	Failed in test			
	2.0 m/o Y_2O_3	2900°F	2 hrs	5.65	22.96	823	-101		ionic uncertain
						860	0		
						949	+382		
						1138	+478	>5	
	5.0 m/o Y_2O_3	2900°F	2 hrs	5.93	14.24	<692	erratic neg		ionic
						692	-360		
						786	0		
						878	+379		
						1001	+388		
						1151		5.75	
						1185		4.45	
						1218	+309	3.99	
						1233		3.64	

APPENDIX

TABLE AI (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	$7^{m}/o\ Y_2O_3$	3000°F	2 hrs	5.64	15.5	942 1020 1140 1223	+366 +263 +375 +331	5.1	ionic
	$10^{m}/o\ Y_2O_3$	3000°F	2 hrs	5.19	20.7	960 1084 1140 1198 1223	+519 -61 +41 +294	5.0	ionic

Base Material	Addition	Firing Conditions Temp.	Time	Atmosphere	Shrinkage	Temp °C	Seebeck Coefficient	Resistivity ohm-cm
CeO_2	$0.1^{m}/o\ UO_2$	2200°F	2 hrs	argon	0.65	all temps	very large and erratic	>5
	$0.2^{m}/o\ UO_2$	2200°F	2 hrs	argon	0.65	all temps	very large and erratic	>5
	$0.5^{m}/o\ UO_2$	2200°F	2 hrs	argon	0.45	all temps	very large and erratic	>5
	$1.0^{m}/o\ UO_2$	2200°F	2 hrs	argon	0.5	all temps	very large and erratic	>5
	$2.0^{m}/o\ UO_2$	2200°F	2 hrs	argon	0.7	all temps	very large and erratic	>5
	$5.0^{m}/o\ UO_2$	2200°F	2 hrs	argon	0.7	508°C only reading that could be obtained	+361	>5

TABLE AII

Summary of Ceramic and Electrical Properties of Lithium Metatitanate and Its Analogues

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
Li₂TiO₃		2400°F	3 hrs	3.86 g/cm³	3.27%	<800°C 950 1050 1215	erratic, neg. +2173uv/°C +2514 +1459	>5 ohm-cm	ionic, uncertain
	0.1 m/o ZnO	2400°F	3 hrs	2.82	14.7	<800 950 981 1135 1215	erratic, neg. +2040 0 −588 −1172	>5	mixed, uncertain
	0.2 m/o ZnO	2400°F	3 hrs	2.85	15.1	<800 950 1215	erratic, neg. +1639 +326	>5	ionic uncertain
	0.5 m/o ZnO	2400°F	3 hrs	2.85	13.4	700 978 1215	erratic, neg. +2000 +87	>5	ionic uncertain
	1.0 m/o ZnO	2400°F	3 hrs	2.87	13.7	700 980 1215	erratic, neg. +1100 +1300	>5	ionic uncertain
	2.0 m/o ZnO	2400°F	3 hrs	2.90	11.8	(~700 (~1000	erratic, large neg. erratic, large pos.	>5	unknown
	5.0 m/o ZnO	2400°F	3 hrs	2.93	12.3	(~1200	erratic, large neg.		
	0.1 m/o MgO	2400°F	3 hrs	3.03	12.7	<950 950 1012 1152	erratic, pos. 0 +779 +897	>5	ionic, uncertain

TABLE AII (continued)

Summary of Ceramic and Electrical Properties of Lithium Metatitanate and Its Analogues

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
Li_2TiO_3	0.2 m/o MgO	2400°F	3 hrs	2.85 g/cm³	13.2	<870 870 916 1190	erratic, neg. 0 >+775 >+1490	>5 ohm-cm	mixed, uncertain
	0.5 m/o MgO	2400°F	3 hrs	3.15	11.3	<914 914 986 1080	erratic, pos. >+1470 >+770 +1085	>5	ionic, uncertain
	1.0 m/o MgO	2400°F	3 hrs	2.88	10.2	<968 968 1140	erratic, neg. 0 +1094	>5	mixed, uncertain
	2.0 m/o MgO	2400°F	3 hrs	2.87	11.3	<704 704 820 942 1206	erratic, neg. 0 +456 >+825 >+925	>5	mixed, uncertain
	5.0 m/o MgO	2400°F	3 hrs	2.88	12.3	<723 723 924 1122	erratic, pos. >+943 >+1100 +1017	>5	ionic uncertain
	0.1 m/o SnO	2400°F	3 hrs	2.83	15.2	<852 852 1046 1173	erratic, neg. -1175 -1130 -24	>5	electronic, uncertain
	0.2 m/o	2400°F	3 hrs	2.83	13.4	<746 746 861 1028 1164	erratic, neg 0 >+1220 >+1785 >+1960	>5	ionic uncertain

TABLE AII (continued)

Summary of Ceramic and Electrical Properties of Lithium Metatitanate and Its Analogues

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
Li₂TiO₃	0.5 m/o SnO	2400°F	3 hrs	2.86	12.6	<788 893 1020 1168	erratic + >+1350⁻ >+2222 >+1695	>5 ohm-cm	ionic uncertain
	1.0 m/o SnO	2400°F	3 hrs	2.89	11.3	<843 843 959 1207	erratic, neg >|-1315| -3480 -253	>5	electronic, uncertain
	2.0 m/o SnO	2400°F	3 hrs	2.95	8.5	<843 843 888 1046 1198	erratic, neg >+2600 >+2440 >+1200 >+952	>5	ionic, uncertain
	5.0 m/o SnO	2400°F	3 hrs	3.04	5.1	742 870 981 1063 1164	-282 -297 -276 -277 -305	>5	electronic, uncertain
	0.1 m/o NiO	2400°F	3 hrs	2.83	14.6	820 843 875	erratic, neg. >+1043 >+1000	>5	ionic uncertain
	0.2 m/o NiO	2400°F	3 hrs	2.83	14.4	816 875 1003 1164	erratic, ± >+1470 >+2220 >+5000		ionic uncertain
	0.5 m/o NiO	2400°F	3 hrs	2.83	14.5	<676 732 932 1046 1156	erratic, neg. >+1053 >+1265 >+1493 >+1515	>5	ionic uncertain

TABLE AII (continued)

Summary of Ceramic and Electrical Properties of
Lithium Metatitanate and Its Analogues

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density g/cm³	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
Li₂TiO₃	1.0 m/o NiO	2400°F	3 hrs	2.84	14.5	820 895 976 1173	erratic, neg. +1077 0 -536	>5 ohm-cm	mixed, uncertain
	2.0 m/o NiO	2400°F	3 hrs	2.83	15.6	<816 976 1182	erratic, neg. +1960 +2630	>5	ionic, uncertain
	5.0 m/o NiO	2400°F	3 hrs	2.83	16.5	<816 932 1046 1063 1190	erratic, neg. +2100 0 -1667 -311	>5	mixed, uncertain
	0.1 m/o Bi₂O₃	2200°F	2 hrs	2.99	2.63	<916 916 1124	erratic, neg. -980 0	>5	mixed, uncertain
	0.2 m/o Bi₂O₃	2200°F	2 hrs	2.97	3.56	842 1028	erratic, ± +901	>5	ionic, uncertain
	0.5 m/o Bi₂O₃	2200°F	2 hrs	2.92	4.53	709 860 1028	erratic, neg. +530 +750	>5	ionic, uncertain
	1.0 m/o Bi₂O₃	2200°F	2 hrs	2.91	8.28	<770 770 916 1028	erratic, neg. -267 0 +1333	>5	mixed, uncertain
	2.0 m/o Ba₂O₃	2200°F	2 hrs	2.92	7.07	<994 994 1012 1080	erratic, neg. -372 0 +892	>5	mixed, uncertain
	5.0 m/o Bi₂O₃	(Unavailable)				<916 916 1050	erratic, pos. +224 +1449	>5	ionic, uncertain

APPENDIX

TABLE AII (continued)

Summary of Ceramic and Electric Properties of
Lithium Metatitanate and Its Analogues

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density g/cm³	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
Li₂TiO₃	0.1 m/o ZrO₂	2400°F	3 hrs.	2.83	14.7	<700 920 1016 1122 1135 1164 1220	erratic, neg. 0 +844 +1200 +1215 +1164 +932	>5 ohm-cm	ionic, uncertain
	0.2 m/o ZrO₂	2400°F	3 hrs	2.85	12.8	<700 950 1140 1215	erratic, neg. 0 -1246 -412	>5	electronic, uncertain
	0.5 m/o ZrO₂	2400°F	3 hrs	2.87	12.7	<700 788 950 1215	erratic, neg. +1000 +438 +885	>5	ionic, uncertain
	1.0 m/o ZrO₂	2400°F	3 hrs	2.90	10.1	<700 778 994 1122 1206	erratic, neg. 0 +1400 0 -700	>5	mixed, uncertain
	2.0 m/o ZrO₂	2400°F	3 hrs	2.94	6.4	<700 994 1206	erratic, neg. >+2700 +1400	>5	ionic, uncertain
	5.0 m/o ZrO₂	2400°F	3 hrs	3.04	4.2	<700 906 976 1004 1215	erratic, neg. >+2100 0 -1910 -1391	>5	mixed, uncertain
	0.1 m/o CeO₂	2400°F	3 hrs	2.86	14.0	<700 960 1164	erratic, neg. +1800 +714	>5	ionic, uncertain

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TABLE AII (continued)

Summary of Ceramic and Electric Properties of
Lithium Metatitanate and Its Analogues

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
Li_2TiO_3	$0.2^{m}/o\ CeO_2$	2400°F	3 hrs	g/cm³ 2.86	13.1	<700	erratic, neg.		unknown
						826	+3000		
						960	0		
						1012	-634		
						1088	0		
						1215	+1258	>5 ohm-cm	
	$0.5^{m}/o\ CeO_2$	2400°F	3 hrs	2.91	9.8	<700	erratic, neg.		ionic, uncertain
						960	+2000		
						1200	+1105	>5	
	$1.0^{m}/o\ CeO_2$	2400°F	3 hrs	2.90	10.9	<700	erratic, neg.		ionic, uncertain
						960	+2000		
						1200	+927	>5	
	$2.0^{m}/o\ CeO_2$	2400°F	3 hrs	2.93	10.8	<700	erratic, neg.		ionic, uncertain
						960	+1700		
						1215	+895	>5	
	$5.0^{m}/o\ CeO_2$	2400°F	3 hrs	3.03	10.4	<700	erratic, neg.	628	ionic
						750	-	63.2	
						898	-	-	
						960	+1800	19.6	
						978	-	25.5	
						1080	-	-	
						1090	+957	23.4	
						1170	-	25.7	
						1200	-	-	
						1215	+1400	-	
	$4^{m}/o\ CeO_2$	2400°F	2 hrs.	3.13	4.62	842	>|-1450|		electronic, uncertain
						986	>|-2040|		
						1080	>|-3125|		
						1206	-663	>5 ohm-cm	
	$7^{m}/o\ CeO_2$	2400°F	2 hrs	3.25	4.70	843	>+1410		ionic, uncertain
						1046	>+2080		
						1164	>+1205	>5	

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TABLE AII (continued)

Summary of Ceramic and Electric Properties of Lithium Metatitanate and Its Analogues

Base Material	Addition	Sintering Condition Temp.	Time	Bulk Density g/cm3	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
Li₂TiO₃	10 m/o CeO₂	2400°F	2 hrs	3.38	4.23	<850 950 1106 1182	erratic, neg. +1180 0 -2250	>5 ohm-cm	Mixed, uncertain
		2400°F	2 hrs	2.81	14.99	<784 784 964 1220	erratic, neg 0 +2666 +1160	>5	ionic, uncertain
	0.1 m/o ThO₂	2400°F	2 hrs	2.79	16.37	<802 802 876 1016	erratic, neg. 0 +1424 +127	>5	ionic, uncertain
	0.2 m/o ThO₂	2400°F	2 hrs.	2.79	17.13	<765 765 839 1016 1220	erratic, neg. 0 +1700 +3000 +1000	>5	ionic, uncertain
	0.5 m/o ThO₂	2400°F	2 hrs	2.87	13.53	<764 764 829 875 1050	erratic, neg. 0 +1118 +464 +87	>5	ionic or mixed, uncertain
	1.0 m/o ThO₂	2400°F	2 hrs	2.87	14.98	<820 820 937 1220	erratic, neg. 0 +893 +1643	>5	ionic, uncertain
	2.0 m/o ThO₂	2400°F	2 hrs	2.88	16.11	<790 793 937 1220	erratic, neg. -860 -1099 -1200	>5	electronic, uncertain
	5.0 m/o ThO₂	2400°F	2 hrs	2.51	30.90 A-23	<820 821 972 1228	erratic, neg. -1342 0 +1877	>5	mixed uncertain

TABLE AII (continued)

Summary of Ceramic and Electric Properties of Lithium Metatitanate and Its Analogues

Base Material	Addition	Sintering Condition Temp.	Time	Bulk Density g/cm³	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
Li₂TiO₃	0.1 m/o Nb₂O₅	2400°F	3 hrs	2.91	14.5	<700	erratic, neg.		ionic, uncertain
						964	+1900		
						1050	+705	>5 ohm-cm	
						1215	+113		
	0.2 m/o Nb₂O₅	2400°F	3 hrs	2.94	11.7	<700	erratic, neg.		ionic, uncertain
						970	+1700		
						1070	0		
						1215	+241	>5	
	0.5 m/o Nb₂O₅	2400°F	3 hrs	3.00	4.1	<700	erratic, neg.		ionic, uncertain
						950	+1600		
						1070	+1135	>5	
						1215	+787		
	1.0 m/o Nb₂O₅	2400°F	3 hrs	3.03	3.3	<700	erratic, neg.		ionic, uncertain
						852	+3000		
						950	+1500	>5	
						1215	+577		
	2.0 m/o Nb₂O₅	2400°F	3 hrs	3.09	2.9	<700	erratic, neg.		ionic, uncertain
						850	+4000		
						950	+1250		
						1215	+650	>5	
	5.0 m/o Nb₂O₅	2400°F	3 hrs	3.24	2.8	<700	erratic, neg.		ionic, uncertain
						950	+1500		
						1215	+370	>5	
	0.1 m/o Ta₂O₅	2400°F	3 hrs	2.98	8.9	<700	erratic, neg.		mixed, uncertain
						900–1000	+2300		
						1050	0		
						1200	+1000	>5	
	0.2 m/o Ta₂O₅	2400°F	3 hrs	2.95	7.3	<700	erratic, neg.		mixed, uncertain
						850	0		
						1000	-1000		
						1050	0		
						1200	+500	>5	

TABLE AII (continued)

Summary of Ceramic and Electric Properties of
Lithium Metatitanate and Its Analogues

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density g/cm^3	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
Li$_2$TiO$_3$	0.5 ^{m}/o Ta$_2$O$_5$	2400°F	3 hrs	3.06	3.7	<700 1050 1190 1200	erratic, neg. / +2300 0 +323	>5 ohm-cm	mixed, uncertain
	1.0 ^{m}/o Ta$_2$O$_5$	2400°F	3 hrs	3.12	3.2	924 986 1030 1056 1114 1198	>|-1700| 0 +537 0 -415 -73	>5	mixed, uncertain
	2.0 ^{m}/o Ta$_2$O$_5$	2400°F	3 hrs	3.17	4.6	942 960 1050 1122 1198 1224	erratic, neg. +1900 0 -473 0 +200	~0.7	mixed
	5.0 ^{m}/o Ta$_2$O$_5$	Failed							
Li$_2$SnO$_3$		2300°F	2 hrs	4.36	13.2	<742 742 870 1033 1182	erratic, neg. 0 +600 +884 +700	>5	ionic,
LiAlO$_2$		2300°F	2 hrs	2.04	19.1	842 986 1080 1206	>|-1450| >|-2040| >|-3125| -663	>5	electronic, uncertain

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TABLE AIII

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density g/cm³	Porosity	Temperature °C	Seebeck Coefficient uv/°C	Resistivity ohm-cm	Conduction
BaTiO₃		2500°F	2 hrs	5.67	5.16%	1232 / 1106 / 986 / 888 / 770 / <770	+439 / +628 / +962 / +1098 / +672 / erratic ±	>5	unknown
	0.1 m/o La₂O₃	2400°F	0 hrs	5.54	7.28	742 / 915 / 1236	-638 / -958 / -566	>5	electronic, uncertain
	0.2 m/o La₂O₃	2400°F	0 hrs	5.84	0.047	750 / 980 / 1219	-929 / -742 / -628	>5	electronic, uncertain
	0.5 m/o La₂O₃	2500°F	2 hrs	5.34	7.49	<960 / 960 / 1174 / 1256	erratic, neg / -1328 / -1171 / -1203	>5	electronic, uncertain
	1.0 m/o La₂O₃	2700°F	2 hrs	5.54	0.14	<915 / 915 / 1030 / 1174	erratic, neg / -969 / -860 / -1087	>5	electronic, uncertain
	2.0 m/o La₂O₃) / 5.0 m/o La₂O₃)	Failed							
	0.1 m/o Nb₂O₃	2500°F	2 hrs	Unavailable		<906 / 906 / 942 / 1100	erratic, neg / -981 / 0 / -676	>5	electronic, uncertain
	0.2 m/o Nb₂O₃	Failed							
	0.5 m/o Nb₂O₃	2600°F	2 hrs	5.42	4.66	<745 / 745 / 946 / 1220	erratic, neg / -1754 / -1951 / -2976	>5	electronic, uncertain

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TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	1.0 m/o Nb_2O_5	2500°F	2 hrs	5.22	7.32	<788 788 862 >862	erratic, neg -610 -1224 very large, neg	 >5	electronic uncertain
	2.0 m/o Nb_2O_5	2500°F	2 hrs	5.50	0.0	<750 750 824 950	erratic, neg -764 -763 -328		electronic uncertain
	5.0 m/o Nb_2O_5	2700°F	2 hrs	5.17	8.06	>950 <836 836 1046 1206	erratic, + erratic, pos. +980 0 +221	>5 >5	ionic uncertain
$BaTiO_3$	0.1 m/o Sb_2O_5	2400°F	0 hrs	5.73	0.73	<780 780 960	erratic, neg -139 -425	 >5	electronic uncertain
	0.2 m/o Sb_2O_5	2400°F	0 hrs	5.69	1.05	<960 960 1164	erratic, neg -778 -767	 >5	electronic uncertain
	0.5 m/o Sb_2O_5	2500°F	2 hrs	5.52	0.65	<1050 1050 1240	erratic, neg -757 -651	 >5	electronic uncertain
	1.0 m/o Sb_2O_5	2500°F	2 hrs	5.66	0.00	<1050 1050 1240	erratic, neg -827 -807	 >5	electronic uncertain
	2.0 m/o Sb_2O_5	2500°F	2 hrs	5.23	0.00	750 870 1002 1206	-133 -647 -1090 -800	 >5	electronic uncertain

APPENDIX
TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	5.0 m/o Sb$_2$O$_3$	2500°F	2 hrs	5.62	0.00	<600 825 >825	erratic, neg -770 very large neg.	>5	electronic uncertain
BaTiO$_3$	0.1 m/o CeO$_2$	2500°F	2 hrs	5.31 g/cm^3	3.33	<714 950 1140 1240	erratic, neg +395 0 -519	>5	unknown
	0.2 m/o CeO$_2$	2500°F	2 hrs	5.34	3.34	<679 852 1198 1240	erratic, neg +934 0 +107	>5	unknown
	0.5 m/o CeO$_2$	2500°F	2 hrs	5.27	6.22	1012 1050 1215	erratic, neg -767 -861	>5	electronic uncertain
	1.0 m/o CeO$_2$	2600°F	2 hrs	5.38	6.20	1012 1050 1215	erratic, neg -780 -738	>5	electronic uncertain
	2.0 m/o CeO$_2$	2600°F	2 hrs	5.41	4.31	986 1038 1215	erratic, neg -381 -833	>5	electronic uncertain
	5.0 m/o CeO$_2$	2600°F	2 hrs	5.36	6.67	1038 1172 1215	erratic, neg -850 -772	>5	electronic uncertain
LaCrO$_3$		3000°F	2 hrs	6.46 g/cm^3	0.0%	582°C 650 819 906 967 1032	+634 μv/°C +629 +288 +640 +650 +695	4.32 ohm-cm 3.59 3.26	ionic

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APPENDIX
TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
0.1 m/o TiO₂	3000°F	2 hrs	6.31	0.7±	592	+571		ionic
					708	+563		
					874	+541	3.65	
					963	558	1.97	
					1041			
					1100	516		
					1231	574		
0.2 m/o TiO₂	Failed to sinter							
0.5 m/o TiO₂	Failed to sinter							
1.0 m/o TiO₂	Failed to sinter							
2.0 m/o TiO₂	Failed to sinter							
5.0 m/o TiO₂	3000°F	2 hrs	5.52	13.2	570	+532		ionic
					724	+522	2.74	
					881	+541	2.03	
					998	+554		
					1134	+565		
0.1 m/o ZrO₂	3000°F	2 hrs	5.40	17.73	592	+560		ionic
					810	+547		
					928	+	2.38	
					945	+568		
					1050	+366	2.22	
					1109			
					1126	+591	1.55	
					1216			
0.2 m/o ZrO₂	3000°F	2 hrs	5.87	8.48	596	+580		ionic, uncertain
					810	+553		
					945	+584		
					1041	+615		
					1159	+595	> 5 ohm-cm	

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TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
0.5 m/o ZrO$_2$	3000°F	2 hrs	5.44	16.85	677	+547		ionic
					777	+533		
					959	+564		
					1030	+555		
					1123	+532		
					1166		2.05	
					1205		3.12	
					1213	+560		
1.0 m/o ZrO$_2$	3000°F	2 hrs	5.94	6.96	594	+491		ionic
					814	+501		
					936	+509		
					1020	+516		
					1056		0.98	
					1112	+449		
					1171		1.08	
					1218	+454		
					1240		0.84	
2.0 m/o ZrO$_2$	3000°F	2 hrs	6.34	10.17	684	+543		ionic
					798	+557		
					904	+585		
					1099	+628		
					1216		1.21	
5.0 m/o ZrO$_2$	3000°F	2 hrs	6.20	1.88	670	+529		ionic
					762		1.38	
					768	+530		
					845		1.81	
					866	+532		
					964	+554		
					968		1.33	
					1072	+545		
					1172		1.15	
					1248		1.26	

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TABLE AIII (continued)

Summary of Ceramics and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	0.1 m/o SnO₂	Failed to sinter							
	0.2 m/o SnO₂	3000°F	2 hrs	644	0.22	574	+587	3.61	ionic
						668		2.77	
						687	+586	2.26	
						760			
						807	+602		
						859	+522		
						963	+637		
						1072	+689		
						1182			
	0.5 m/o SnO₂	3000°F	2 hrs	5.66	10.32	633	+138		ionic uncertain
						706	+671		
						799	+626		
						843	-277		
						894	>|-833|		
						943	+667		
						1100	+711		
						1213	+707	>5	
	1.0 m/o SnO₂	3000°F	2 hrs	4.46	33.2	770	+525		ionic
						861	+548		
						968	+584		
						1080	+606	1.9	
						1140			
						1182	+663		
	2.0 m/o SnO₂	3000°F	2 hrs	6.38	0.11	702	+631	4.58	ionic
						749			
						826	+658		
						841		4.07	
						942	+647	3.67	
						1036	+656		
						1053		3.40	
						1143		3.18	
						1168	+601		
						1235		2.93	

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TABLE AIII (continued)

Summary of Ceramics and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	5.0 m/o SnO$_2$	3000°F	2 hrs	6.40	0.02	594	+568		ionic
						734	+555		
						850	+569		
						963	+574		
						982		2.09	
						1072	+585		
						1095		2.09	
						1185		1.91	
						1200	+577		
LaCrO$_3$		3000°F	2 hrs	6.47	0	602	+628		ionic
						689	+600		
						766	+630	3.52	
						938	+684	3.80	
						1013	+652	3.38	
						1166	---	3.97	
						1223	---	3.61	
	0.1 m/o CeO$_2$	Failed to sinter							
	0.2 m/o CeO$_2$	3000°F	2 hrs	6.56	0	592	+672		ionic
						792	+667		
						1019	+698		
						1034		4.52	
						1119	+713		
						1226	+705		
						1255		4.03	
	0.5 m/o CeO$_2$	3000°F	2 hrs	6.52	0.05	758	+629		ionic
						957	+661		
						985		5.35	
						1063		5.23	
						1089	+663	4.65	
						1154			
						1193	+679		
						1257		4.08	

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TABLE AIII(continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	$1.0\,^{m}/oCeO_2$	3000°F	2 hrs	4.46	33.30	648		3.68	ionic
						690	+522		
						790		3.45	
						810	+512		
						909		2.89	
						936	+509		
						1030		2.08	
						1034	+529		
						1117		2.65	
						1151	+541		
						1210		2.24	
	$2.0\,^{m}/oCeO_2$	3000°F	2 hrs	6.47	0	1065		4.67	ionic
						1163		3.66	
						1230		3.98	
						1173	+288		
						1049	+723		
						958	+691		
						842	+675		
						730	+665		
						570	+708		
	$5\,^{m}/oCeO_2$	3000°F	2 hrs	5.96	6.62	664	+595	5.76	ionic
						700			
						762	+588		
						876	+580		
						910		2.47	
						975	+574		
						1048		3.45	
						1097	+545		
						1206	+590		
						1223		2.37	

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TABLE AIII(continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
$YCrO_3$		3000°F and 3100°F	2 hrs 2 hrs	3.82	32.7	<1002 1002 1028 1219	erratic, pos +371 +372 +1070	>5	ionic uncertain
	.1 ^{m}/o CeO_2	3000°F and 3100°F	2 hrs 2 hrs	4.34	22.8	806 <806 897 1080 1224	+erratic, pos +831 +1000 +1551 +976	>5	ionic uncertain
	.2 ^{m}/o CeO_2	3000°F and 3100°F	2 hrs 2 hrs	4.03	28.9	<994 994 1054 1130	erratic,+- <|-228| 0 <|+367|	>5	mixed, uncertain
	.5 ^{m}/o CeO_2	3000°F and 3100°F	2 hrs 2 hrs	4.36	22.6	816 888 1032 1169	erratic, pos +967 +1428 +1108	>5	ionic uncertain
	1 ^{m}/o CeO_2	3000°F and 3100°F	2 hrs 2 hrs	3.98	29.9	<1008 1008 1206	erratic, pos >+2326 >|-1613|	>5	mixed uncertain
	2 ^{m}/o CeO_2	3000°F and 3100°F	2 hrs 2 hrs	3.41	40.1	<942 942 1050 1218	large, neg >|-1408| >|-1450| +915	>5	mixed uncertain
	5 ^{m}/o CeO_2	3000°F and 3100°F	2 hrs 2 hrs	3.33	41.5	<1008 1008 1218	erratic, neg -1605 +1171	>5	mixed uncertain

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TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Condition
	.1 m/o TiO$_2$	3000°F	2 hrs	4.90	10.2	1218 / 942 / 824 / <824	+1132 / +906 / +943 / erratic, pos	>5	ionic uncertain
	.2 m/o TiO$_2$	3000°F	2 hrs	4.75	14.0	1218 / 994 / <994	+970 / 0 / erratic ±	>5	mixed uncertain
	.5 m/o TiO$_2$	3000°F	2 hrs	5.05	8.0	1218 / 1072 / <1072	+1113 / -1900 / very erratic, +	>5 ±	mixed uncertain
	1 m/o TiO$_2$	3000°F	2 hrs	5.09	5.9	1218 / 1164 / <1164	+1160 / +2272 / erratic, pos	>5	ionic uncertain
	2 m/o TiO$_2$	3000°F	2 hrs	5.46	3.2	1218 / 1172 / 1130 / 1012 / <1012	+128 / 0 / -223 / -903 / erratic, neg	>5	mixed uncertain
	5 m/o TiO$_2$	3000°F	2 hrs	4.41	21.3	1173 / 986 / 870 / <870	+867 / +960 / +830 / erratic, pos	>5	ionic uncertain
	.1 m/o ZrO$_2$	3100°F	2 hrs	4.66	17.37	1038 / 924 / 842 / <842	>+1220 / >+952 / +788 / very large, pos.	>5	ionic, uncertain
	.2 m/o ZrO$_2$	3100°F	2 hrs	4.63	17.8	986 / 897 / <897	+738 / <+512 / erratic, ±	>5	ionic uncertain

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TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Simple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	$.5\,{}^{m}/oZrO_2$	3100°F	2 hrs	4.70	14.5	1198	+1125	>5	ionic uncertain
						1072	+2021		
						942	>+1429		
						824	>+1150		
						714	>+1052		
						<714	erratic, pos		
	$2\,{}^{m}/oZrO_2$	3100°F	2 hrs	4.06	29.0	1164	+703	>5	ionic uncertain
						1096	+337		
						<1096	erratic+		
	$5\,{}^{m}/oZrO_2$	3100°F	2 hrs	4.38	23.8	1218	>+787	>5	mixed uncertain
						1106	+1061		
						1012	0		
						942	-950		
						<942	erratic, neg		
$PbNb_2O_6$		2150°F	2 hrs	6.07	5.48	1218	-1020	>5	mixed uncertain
						1160	-1961		
						1096	0		
						1008	+2375		
						937	+978		
						830	>+1587		
						<830	very large, pos		
	$0.1\,{}^{m}/oCdO$	2200°F	2 hrs	6.11	4.73	680	-448		mixed uncertain
						726	0		
						736	+350		
						838	>|+1375|		
						998	+812		
						1066	0		
						1143	-519	>5	

APPENDIX

TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	0.2 m/o CdO	2200°F	2 hrs	6.10	4.32	<726	erratic, neg		mixed uncertain
						792	>|-1138|		
						902	0		
						910	+428		
						954	0		
						972	-194		
						1024	-568	>5	
	0.5 m/oCdO	2200°F	2 hrs	5.83	7.58	<754	erratic, neg		electronic uncertain
						754	-411		
						928	>|-2061|		
						1066	-2500		
						1168	-1060	>5	
	1.0 m/oCdO	2200°F	2 hrs	5.70	10.54	<755	erratic, neg		mixed uncertain
						755	>|-1121|		
						892	-1188		
						963	0		
						980	+216		
						1016	0		
						1040	-73		
						1154	-712	>5	
	2.0 m/oCdO	2200°F	2 hrs	5.33	17.41	<736	erratic, neg		electronic
						736	-771		
						797		21,200	
						801	>|-1560|		
						892	>|-1821|		
						897		6,359	
						1016	-1141		
						1088		399	
						1152	-1121		
						1198		64	

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TABLE AIII(continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
5 m/o CdO	2200°F	2 hrs	4.91	24.8	<726	erratic, neg		electronic uncertain
					726	>|-1072|		
					782	>|-1141|		
					864	>|-1236|		
					1006	-800		
					1118	-708	>5	
0.1 m/o Bi₂O₃	2200°F	2 hrs	6.06	4.86	<724	erratic, neg		electronic uncertain
					724	-683		
					800	-415		
					910	-1720		
					1170	-994	>5	
0.2 m/o Bi₂O₃	2200°F	2 hrs	6.09	4.93	<718	erratic, neg		electronic uncertain
					718	-498		
					792	>|-1138|		
					892	>|-1228|		
					1168	-813	>5	
0.2 m/o Bi₂O₃	2200°F	2 hrs	6.09	4.93	<718	erratic, neg		electronic uncertain
					718	-498		
					792	>|-1138|		
					892	>|1228|		
					1168	-813	>5	
0.5 m/o Bi₂O₃	2200°F	2 hrs	5.74	6.54	<715	erratic, neg		electronic
					715	-685		
					732		69,500	
					770	-1143		
					800		23,000	
					856	>|-2178|		
					915		3,798	
					1015	-3285	766	
					1097		244	
					1142	-2098		
					1215		55	

APPENDIX

TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	1.0 ^{m}/oBi$_2$O$_3$	2200°F	2 hrs	5.63	9.34	<698	erratic, neg		electronic uncertain
						698	-1090		
						782	>|-1290|		
						836	>|-1397|		
						980	-771		
						1168	-780	>5	
	2.0 ^{m}/oBi$_2$O$_3$	2200°F	2 hrs	5.83	7.59	<762	erratic, neg		electronic uncertain
						762	-1215		
						862	>|-1724|		
						936	-1233		
						1150	-522	>5	
	5 ^{m}/oBi$_2$O$_3$	2200°F	2 hrs	5.44	15.23	<670	erratic, neg		electronic uncertain
						670	-1029		
						845	-745		
						928	-454		
						1118	-744	>5	
PbNb$_2$O$_6$		2150°F	2 hrs	6.06	5.26	1218	-921	>5	mixed uncertain
						1192	0		
						1110	+1000		
						1032	+1979		
						924	+1257		
						866	> +1333		
						<866	erratic, pos.		
	0.1Sb$_2$O$_5$	2150°F	2 hrs	6.00	5.58	732		84,300	electronic
						793		23,600	
						<800	erratic, neg		
						800	>|-1751|		
						915		3.699	
						972	>|-2705|		
						1016		801	
						1100		2.55	
						1160	>|-1930|		
						1207		68	

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TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	0.2 m/o Sb_2O_3	2150°F	2 hrs	5.91	5.90	<782	erratic, neg		mixed
						782	-910		uncertain
						874	0		
						936	>+1579		
						1058	0		
						1142	-641	>5	
	0.5 m/o Sb_2O_3	2150°F	2 hrs	5.98	5.20	<754	erratic, neg		electronic
						754	-279		uncertain
						812	-260		
						910	-1154		
						1143	-1272	>5	
	1.0 m/o Sb_2O_3	2150°F	2 hrs	5.58	7.19	<708	erratic, neg		unknown
						708	>|-1040|		
						762	0		
						802	+668		
						846	0		
						863	-167		
						892	0		
						945	+599		
						1066	0		
						1100	-264	>5	
	2.0 m/o Sb_2O_3	Unavailable				<782	erratic, neg		electronic
						782	>|-1176|		uncertain
						874	>|-1277|		
						998	-505		
						1151	<|-874|	>5	

APPENDIX

TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	$5.0^{m}/oSb_2O_5$	2150°F	2 hrs	6.04	4.44	<891	erratic, neg		electronic uncertain
						891	-909		
						954	-1056		
						1006	-788	>5	
						1151	-791	>5	
$PbNb_2O_6$		2200°F	2 hrs	6.00	5.69	1214	-980	>5	mixed uncertain
						1156	0		
						1054	+1885		
						<1054	erratic, pos		
	$0.1^{m}/oMoO_3$	2150°F	2 hrs	5.96	5.82	782	>|-1494|		mixed uncertain
						874	>|-1666|		
						901	0		
						1032	+69		
						1041	0		
						1151	-661	>5	
	$0.2^{m}/oMoO_3$	2150°F	2 hrs	5.86	5.72	880	>|-1834|		electronic uncertain
						1006	-1896		
						1185	-836	>5	
	$0.5^{m}/oMoO_3$	2150°F	2 hrs	5.97	5.82	782	>|-1474|		electronic uncertain
						874	>|-1721|		
						998	-1585		
						1168	-796	>5	
	$1.0^{m}/oMoO_3$	2150°F	2 hrs	5.22	5.08	820	<|+1111|		mixed uncertain
						864	<|+1165|		
						936	0		
						962	-486		
						1092	-895	>5	
	$2.0^{m}/oMoO_3$	2150°F	2 hrs	6.07	5.78	<968	erratic, neg		electronic uncertain
						968	-1468		
						981	-1808	>5	

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TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	5.0 m/o MoO₃	2150°F	2 hrs	5.95	6.27	968 1088 1190	-1377 -1400 -939	 > 5 > 5	electronic uncertain
PbNb₂O₆		2200°F	2 hrs	6.13	4.98	1218 1122 1002 <1002	-852 -900 -1215 erratic, neg	> 5 > 5	ionic uncertain
	0.1 m/o WO₃	2200°F	2 hrs	6.02	6.92	<906 906 968 1061 1206	erratic, neg -304 -624 <|-835| -925	>5	electronic uncertain
	0.2 m/o WO₃	2200°F	2 hrs	5.91	6.79	<896 896 960 1148	erratic, neg -56 -539 -925	>5	electronic uncertain
	0.5 m/o WO₃	2200°F	2 hrs	6.03	3.66	<694 942 1088	erratic, neg -855 -1100	>5	electronic uncertain
	1.0 m/o WO₃	2200°F	2 hrs	5.94	5.00	<902 902 1028 1140	erratic, neg -704 <|-652| <|-865|	>5	electronic uncertain
	2.0 m/o WO₃	2200°F	2 hrs	5.95	5.71	Failed in test			
	5.0 m/o WO₃	2200°F	2 hrs	6.01	4.20	<906 906 1028 1122	erratic, neg 0 >+1050 >+1085	>5	mixed uncertain

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TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
Pb₂Nb₂O₇		2300°F	0 hrs	5.65	20.9	<800 800 844 936 988 1184	erratic, neg +1256 +2912 0 -1600 <-1343|	>5	mixed uncertain
	0.1 m/oCdO	2300°F	0 hrs	5.61	22.8	<773 773 826 910 1015 1159	erratic, neg +632 +1077 0 -833 -738	>5	mixed uncertain
	0.2 m/oCdO	2300°F	0 hrs	5.70	20.2	<764 764 821 989 1143	erratic, neg >|-1242| >|-2645| -641 -692	>5	electronic uncertain
	0.5 m/oCdO	2300°F	0 hrs	5.80	19.8	<736 736 764 838 1144	erratic, neg -931 >|-1092| >|-1176| -665	>5	electronic uncertain
	1.0 m/oCdO	2300°F	0 hrs	5.84	20.2	<726 726 764 802 883 1143	erratic, neg -458 -221 0 -669 -717	>5	electronic uncertain

APPENDIX
TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Material	Addition	Temp.	Time	Density	Porosity	Temperature	Coefficient	Resistivity	Conduction
	$2.0^{m}/oCdO$	2300°F	0 hrs	6.05	19.7	<726 726 874 954 1151	erratic, neg -1088 >|-1639| -340 -697	>5	electronic uncertain
	$5.0^{m}/oCdO$	2200°F	2 hrs	5.22	32.04	<719 719 810 901 988 1151	erratic, neg -572 >|-1114| -1132 -778 <|-747|	>5	electronic uncertain
$Pb_3Nb_2O_7$		2200°F	2 hrs	5.18	40.89	<708 708 746 782 856 901 1126	erratic, neg -395 -116 +240 0 -495 -722	>5	mixed uncertain
	$0.1^{m}/oBi_2O_3$	2200°F	2 hrs	5.53	37.0	<690 690 726 874 1050	erratic, neg -804 -571 >|-1100| -703	>5	electronic uncertain
	$0.2^{m}/oBi_2O_3$	2200°F	2 hrs	5.65	27.3	<746 746 945 1151	erratic, neg -224 -373 -685	>5	electronic uncertain
	$0.5^{m}/oBi_2O_3$	2200°F	2 hrs	5.67	26.0	<724 724 792 810 838 918 1134	erratic, neg -590 0 +790 0 -732 <|-657|	>5	mixed uncertain

APPENDIX
TABLE AIII (continued)
Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	1.0 m/o Bi_2O_3	2200°F	2 hrs	5.77	25.1	<745	erratic, neg		electronic uncertain
						745	> -1154		
						812	> -1256		
						945	-648		
						1111	-670	>5	
	2.0 m/o Bi_2O_3	2200°F	2 hrs	5.76	19.6	<726	erratic, neg		mixed uncertain
						726	-319		
						747	0		
						828	+987		
						892	0		
						980	-706		
						1151	-697	>5	
	5.0 m/o Bi_2O_3	2200°F	2 hrs	6.78	6.21	612	-786		electronic uncertain
						698	> -1200		
						828	> -1300		
						1143	-786	>5	
	0.1 m/o Sb_2O_5	2200°F	2 hrs	5.77	22.9	<755	erratic, ±		mixed uncertain
						755	-35		
						865	+1818		
						910	0		
						1032	-817		
						1142	-810	>5	
	0.2 m/o Sb_2O_5	2200°F	2 hrs	6.03	14.6	<968	erratic, neg		electronic uncertain
						968	-477		
						1088	-591	>5	
	0.5 m/o Sb_2O_5	2200°F	2 hrs	5.78	22.05	<764	erratic, neg		electronic uncertain
						764	> -134		
						857	> -153		
						971	-912		
						1126	-775	>5	

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TABLE AIII(continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	1.0 ^{m}/oSb$_2$O$_5$	2200°F	2 hrs	5.66	25.5	<629 629 708 724 854 918 1118	erratic, neg <|-1836| <|-606| 0 >|+218| 0 -705	 >5	mixed uncertain
	2.0 ^{m}/oSb$_2$O$_5$	2200°F	2 hrs	5.91	20.0	<780 780 864 984 1202	erratic, neg >|-1414| >|-642| -651 -609	 >5	electronic uncertain
	5.0 ^{m}/oSbO$_5$	2200°F	2 hrs	5.70	23.9	<612 612 698 828 1143	erratic, neg -773 >|-137| >|-120| -786	 >5	electronic uncertain
	0.1 ^{m}/oWO$_3$	2200°F	2 hrs	5.6	21.5	<792 792 837 901 1032 1162	erratic, neg -747 -385 -681 -881 -763	 >5	electronic uncertain
	0.2 ^{m}/oWO$_3$	2200°F	2 hrs	5.79	18.6	<782 782 828 904 1015 1151	erratic, neg -676 -463 -391 -741 -721	 >5	electronic uncertain

APPENDIX
TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	$0.5^{m}/oWO_3$	2200°F	2 hrs	5.92	16.6	<810 810 882 892 980 1168	erratic, neg -257 +207 0 -701 -725	>5	mixed uncertain
	$1.0^{m}/oWO_3$	2200°F	2 hrs	5.75	19.4	<810 810 864 971 1168	erratic, neg -862 -812 -766 -645	>5	electronic uncertain
	$2.0^{m}/oWO_3$	2200°F	2 hrs	5.37	23.1	679 736 845 936 1168	-709 -266 +124 -722 <|-482|	>5	mixed uncertain
	$5.0^{m}/oWO_3$	2200°F	2 hrs	4.87	31.8	<670 670 736 835 1106 1169	erratic, neg -425 >|-794| >|-860| -722 <|-110|	>5	electronic uncertain
$Pb_2Nb_2O_7$		2200°F	2 hrs	5.43	24.78	<717 717 847 954 1100	erratic, neg -675 >|-982| -548 -662	>5	electronic uncertain
	$0.1^{m}/oMoO_3$	2200°F	2 hrs	5.24	24.9	>801 801 928 1151	erratic, neg >|-1754| -654 -697	>5	electronic uncertain

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TABLE AIII (continued)

Summary of Ceramic and Electrical Properties of Multiple Oxides

Base Material	Addition	Sintering Conditions Temp.	Time	Bulk Density	Porosity	Temperature	Seebeck Coefficient	Resistivity	Conduction
	$0.2^{m}/oMoO_3$	2200°F	2 hrs	5.87	20.2	<782	erratic, neg		mixed uncertain
						782	-233		
						805	0		
						838	+1109		
						878	0		
						945	-474		
						1134	-726	>5	
	$0.5^{m}/oMoO_3$	2200°F	2 hrs	6.77	27.3	<764	erratic, neg		electronic uncertain
						764	-191		
						856	-74		
						982	-788		
						1117	-655	>5	
	$1.0^{m}/oMoO_3$	2200°F	2 hrs	5.53	23.2	<773	erratic, neg		electronic uncertain
						773	-323		
						874	-614		
						945	-619		
						1143	-690	>5	
	$2.0^{m}/oMoO_3$	2200°F	2 hrs	5.72	20.4	<764	erratic, neg		electronic uncertain
						764	-845		
						819	-598		
						892	-790		
						992	-564		
						1168	-610	>5	
	$5.0^{m}/oMoO_3$	Failed to sinter							